REAL-TIME DIGITAL IMAGING TECHNIQUES
FOR FLOW VISUALIZATION

By

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A Thesis Submitted for the Degree of
Doctor of Philosophy

APRIL 1989
SUMMARY

A real-time digital imaging technique has been applied to smoke flow visualized turbulent flows to provide statistical data concerning bluff body wakes. The 'digital imaging technique' has been successfully applied to the wake of a two-dimensional flat plate, circular cylinder and a jet in a crossflow configuration. A detailed study of the two-dimensional flat plate model involved comparative hot-wire and pressure measurements combined with data from previously published experimental investigations. The results obtained included, intermittency measurements, vortex shedding spectral analyses (autocorrelations), spatial correlations, wake interface statistics and turbulence data. In the majority of cases, the digital imaging technique was found to provide excellent quantitative detail whilst also offering some unique wake interface statistics. The experiments conducted on the circular cylinder model revealed details of secondary vortex shedding and their base-bleed dependence, whilst the jet in a crossflow configuration enabled the imaging technique to be applied to a complex, three-dimensional flow model. The resulting iso-intermittency contour map was produced expediently, and within an experimental period far shorter than could be expected for single-location probe measurements.

In addition to the above-outlined quantitative technique, real-time digital imaging was also applied more qualitatively to the study of dynamic stall on an aerofoil and to the enhancement of high-speed vapour-screen visualizations, both techniques offering the possibility for enhanced quantitative flow studies in future investigations.

Finally, true-colour video digitisation has been exploited in a preliminary study of the quantification of global surface shear stress values using liquid crystal technology. Although in its infancy, the realisation of an experimental procedure along such lines would be of immense benefit to experimental aerodynamic research.
ACKNOWLEDGEMENTS

I would like to thank Dr Norman Toy for his supervision, guidance and friendship over the five years of my research career at the University of Surrey. I am grateful for all of the opportunities made available to me whilst in the Department of Civil Engineering and particularly to Norman for enabling the many overseas visits, throughout Europe and to the U.S.A.

The support of my Head of Department, Prof N Simons in connection with my research is also much appreciated.

Within the Fluids Division, I would like to thank Dr Eric Savory, whose dedication and application to fluid mechanics research over the past five years has achieved so much. The exceptional efforts of Mr Ron Northam, who completed the construction of the smoke tunnel facility 'on-time and to-budget' and who provided continual assistance in the laboratory, are also very much appreciated.

I am also grateful to Mr Lauret Gaudet of RAE Bedford, whose individual efforts often consumed me with enthusiasm, and without whom many avenues of my research would possibly have remained 'fermé'.

I have appreciated the value of friends and colleagues, both present and past, without whom the motivation and desire for academic research may so easily wain. In particular, I would like to thank Dr Steve Moore, A.K., Bahman, Susi, Rennie, Martin, Aymen and Kassem.

Finally, I would like to acknowledge the support of both the Science and Engineering Research Council and the Royal Aerospace Establishment for the financial support that enabled this work to be undertaken.
Dedicated To My Wife

and Families Wisby,

Sharman and Hamilton.
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NOMENCLATURE

AR  Aspect Ratio - Length/Breadth

c  Chord Length, mm

Cp  Drag Coefficient

Cf  Skin Friction Coefficient,

Cp  Pressure Coefficient, \((P_s - P_0)/\frac{1}{2} \rho U_o^2\)

Cpb  Base Pressure Coefficient - Measured on Centreline

Cpmin  Minimum Wake Pressure Coefficient

d  Diameter of Circular Cylinder or Jet Nozzle, mm

d'  Wake Width, mm

D  Breadth of Flat Plate Model, mm

h  LEBU Height above Flat Plate Surface, mm

H  Boundary Layer Shape Factor, \(\theta/\delta^*\)

k  Base Pressure Parameter, \(\sqrt{1 - C_{pb}}\)

Lux  Integral Length Scale, \(\int_{0}^{x} Ru(X) \ dx\)

n,f  Vortex Shedding Frequency, Hz

Ps  Local Pressure on Model Surface

P0  Static Pressure

R,G,B  Primary Colours, Red, Green, Blue

r,g,b  Tristimulus Components Red, Green, Blue

\(R_{(r_1, r_2, r_3)}\)  Spatial Correlation Coefficient, \(\frac{u(x) \ u(x+r)}{u^2(x)}\)

\(R(T)\)  Autocorrelation Coefficient, \(\frac{\int f(t) f(t+\tau) \ dt}{\int f(t) f(t) \ dt}\)

Re  Reynolds Number, \(DU_o/\nu\)

Re_g  Reynolds Number Based on Momentum Thickness, \(\theta U_o/\nu\)

Re_\*  Universal Reynolds Number, \(U_b d'/\nu\)

St  Strouhal Number, \(nD/U_o\)

St_\*  Universal Strouhal Number, \(n d'/U_b\)

t  Time, seconds

U_b  Separated Boundary Layer Mean Velocity, \(kU_o\)

U0  Mean Freestream Velocity in X-Direction, m/s

u  Instantaneous Velocity in X-Direction, m/s

\(\bar{u}\)  Local Mean Velocity in X-Direction, m/s

u'  Velocity Fluctuation in X-Direction, m/s

X  Cartesian Coordinate in Longitudinal Direction

Y  Cartesian Coordinate in Direction Perpendicular to Lateral Direction

Z  Cartesian Coordinate in Lateral Direction
\( \alpha \) Angle of Attack of Wing, Rads

\( \dot{\alpha} \) Rate of Change of Angle of Attack, Rads/s

\( \dot{\alpha}_N \) Non-Dimensional Rate of Change of Angle of Attack, \( \frac{1}{2}c\dot{\alpha}/U_0 \)

\( \delta_{0.99} \) Boundary Layer Thickness - 99% Location of Freestream Velocity, mm

\( \delta^* \) Boundary Layer Displacement Thickness, \( \int_0^{\infty} \left(1 - \frac{u}{U_0}\right) dy \) mm

\( \theta \) Boundary Layer Momentum Thickness, \( \int_0^{\infty} \frac{u^2}{U} \left(1 - \frac{u}{U}\right) dy \) mm

\( \gamma \) Intermittency Factor

\( \tau_w \) Wall Shear Stress, N/m²

\( \mu \) Dynamic Viscosity of Fluid, kg/m s

\( \nu \) Kinematic Viscosity of Fluid, \( \mu/\rho \) m²/s

\( \Phi, \mathcal{E}(n) \) Spectral Energy, \( 4\int_0^{\infty} R(\tau) \cos 2\pi nt \, d\tau \)
CHAPTER ONE

INTRODUCTION

1.1 General Introduction

Flow visualization is, perhaps, the most powerful investigative tool available to researchers in the realm of fluid mechanics. Through the use of an array of visualization techniques, complex flow patterns may be rendered visible, recorded and studied at leisure to enhance the comprehension of a variety of flow mechanisms. Traditional single-location anemometer probes and pressure-sensing devices, whilst offering quantitative flow analysis capabilities over a specified flow period, cannot offer a fraction of the instantaneous, global flow detail visible in such methods as optical and tracer flow visualization. It is, therefore, almost unbelievable that so many analyses of complex flows are undertaken without any attempt of flow visualization, or as may also be the case, visualizations only being called upon once the collected quantitative data becomes too confusing to immediately comprehend. How often, for instance, has a critical model geometry or member spacing ratio been discovered after months (or years) of quantitative analysis, when a preliminary flow visualization study would, perhaps, have revealed the same detail in a matter of days (or minutes)? The present economic climate demands an expedient and beneficial utilisation of all experimental research facilities. Obviously, the possible benefits of conducting flow visualization experiments are significant enough to demand its continuous use in experimental research. At the same time, however, the possible extension of traditional flow visualization techniques to include some form of global flow quantification would appear to offer the possibility of a truly invaluable flow analysis method.
The details reported in this thesis represent the Author's contributions towards the achievement of a quantitative incompressible flow visualization technique. Referred to as the 'Digital Imaging Technique', 'real-time' or continuous digital image analysis has been applied to smoke-visualized flows to produce a variety of quantitative data. Whilst the technique does require specialist digital imaging equipment, its relative cost, combined with an uncomplicated illumination source (5 mW Helium-Neon Laser), would appear insignificant in today's high-technology environment, where experimental expedience is a major priority at all levels of research. In addition to investigating the possible quantitative aspects of smoke flow visualization, the study also provides a non-intrusive flow sensing device that may be particularly applicable to investigations involving 'flow disturbance sensitive' flows such as those involving shear layer instabilities. It may, at the same time, clarify lingering doubts regarding the qualitative interpretation of smoke visualized flows.

From an historical viewpoint the first significant contribution of flow visualization to the realm of fluid mechanics was provided in the fifteenth century by Leonardo da Vinci (reproduced (1923)) who, from detailed flow sketches, was able to postulate anatomical theories concerning the flow of blood through the heart. Other classical examples of visualization have illustrated the flow around a bullet and transition to turbulence in a pipe flow, with the more recent interest in this field (over the last two decades) being recorded at the triennial meetings of the International Symposia on Flow Visualization, the most recent being held in Paris (1986) and the next scheduled meeting being Prague (1989).

Optical flow visualizations, revealing density or refractive index variations in a fluid, have always been recognised as quantitative techniques but, due to the complexity of their analysis, have mostly been interpreted from only a qualitative viewpoint.
Recent advances in holographic interferometry appear to offer further quantitative possibilities (reviewed by Lauterborn and Vogel (1984) and Settles (1986)), with advances towards efficient data analyses being reported by Trolinger (1985), Boyd et al (1985) and Hunter and Collins (1986). Whilst optical methods have generally been criticised for their unavoidable two-dimensional characteristic of integrating flow density information along the optical illumination path, Zien et al (1975) and Snyder and Hesselink (1984) have successfully undertaken three-dimensional flow analyses.

If detectable changes in fluid density do not occur (incompressible flows), an alternative visualization technique using tracer particles may be adopted, which when acted upon by the flow indicate, indirectly, flow motion. In particular, quantitative incompressible flow analysis using smoke contaminants as the flow tracer have been reported by Rosensweig et al (1961) who measured point concentration fluctuations and Fiedler and Head (1966) who presented point intermittency measurements in a turbulent boundary layer. More recently, Borleteau (1984, 1986), Schon (1984), Ohba et al (1984) and Keffer et al (1985) have used digital image analysis to examine the properties of turbulent flows. Gennero and Mathe (1985) reported a real-time edge display system to study vortices which digitised a medium resolution image (280(H) * 192(V) picture elements) to one-bit (binary) grey level. The major problem, however, with all of the aforementioned attempts at digital image analysis has been the inefficient and laborious means of collecting sufficient information to formulate meaningful statistical data. The digital imaging technique presented in this thesis, however, undertakes real-time image analysis of limited flow details to provide an on-line experimental procedure capable of collecting significant data sets. As such, the philosophical approach of the digital imaging technique differs markedly from previously reported visualization techniques, in as much as the visualized flow images are neither recorded nor
are they, in their appearance, immediately revealing to a human observer.

The principle objective of this study was, therefore, to ascertain how digitised, illuminated flow images could be statistically analysed, and having established such methods, discover how well the resultant statistical data compared with traditionally acquired anemometer (hot-wire) information. In addition to the correlation of the results obtained by the two independent analysis procedures, a final decision regarding the applicability of a digital imaging approach to turbulent flow analysis should, of course, also consider the relative experimental efficiencies and initial costs of the proposed techniques.

Having demonstrated the feasibility of the digital imaging technique, this dissertation also presents brief introductions and examples of how digital image analysis and processing may be beneficially applied to other fluid mechanics studies involving various forms of flow visualization, such as high-speed vapour-screen and shear stress sensitive liquid crystal techniques.

The following section of this chapter gives details of the scope of the investigations undertaken, whilst the final section describes the overall format of the thesis.

1.2 Scope of the Present Work

The primary study presented in this dissertation investigates a detailed experimental comparison of the flow statistics associated with the wake of a two-dimensional, thin, sharp-edged flat plate model. The investigations were conducted in a specially commissioned low-speed, open-return smoke tunnel facility (designed by the Author) which, incorporating an efficient smoke filtration system, could be used for continuous smoke flow visualization.
The turbulent flat plate wake structure was visualized by direct injection of smoke contaminant into the near-wake immediately behind the model via a small-bore (10.0 mm diameter) smoke-tube, the illumination being provided by a single-beam 5 mW Helium-Neon laser. The visualized images were viewed by an 'FT-CCD', variable integration period solid state video device, the analogue output from which was digitised in real-time at a rate of 8.0 MHz, to produce digital images of medium resolution (512(H) * 256(V) picture elements) at a standard video rate of fifty fields per second. The general arrangement of the apparatus involved in this study is illustrated below:

The analysis of the digital images was undertaken in real-time via the host Digital Electronic Corporation (DEC) Micro PDP11/73 minicomputer, which could simultaneously access the temporarily stored digital image picture elements. Comparative anemometer data for the turbulent wake statistics were provided by single-sensor hot-wire traverses.
The detailed comparative digital imaging and hot-wire investigations were undertaken over a range of Reynolds numbers from $6.82 \times 10^3$ to $2.73 \times 10^4$ (corresponding to freestream velocities of 2.0 to 8.0 m/s) on the following statistical properties of the flat plate wake:

(i) Intermittency Measurements,
(ii) Autocorrelation Function and Spectral Analyses,
(iii) Spatial Correlation,
(iv) Wake Interface Statistics, and
(v) Mean Fluctuating Turbulence Quantities.

In addition to the comparative studies on the flat plate model, further investigations using the digital imaging technique were undertaken into the frequency relationship of secondary vortex shedding from a circular cylinder and the intermittency contours of a turbulent circular jet issuing into a uniform crossflow.

Finally, further examples of the application of digital imaging to other visualized flows are presented, these investigations being:

(a) Boundary Layer Modification by Passive Means,
(b) Dynamic Stall on an Aerofoil,
(c) High-speed Vapour-Screen Visualization, and
(b) Shear Stress Sensitive Liquid Crystals.

The final section of this introduction describes the general format of this thesis and briefly outlines the main topics discussed in each chapter.

1.3 Organisation of the Thesis

The overall organisation of this thesis may be considered as having two distinct contributions, these being the detailed comparative study of the flat plate using the digital imaging technique and hot-wire anemometry, Chapters Two to
Six inclusive, with Chapter Seven providing a further investigative contribution through the study of alternative flow models and additional visualization enhancements.

The next chapter of this dissertation, Chapter Two, reviews the existing literature relevant to the digital imaging technique and the comparative flow model, the two-dimensional flat plate. It begins with an examination of various flow visualization techniques, the first group of these being optical methods, from which holographic interferometry is indicated as being the technique most applicable to a quantitative flow analysis procedure. The second half of this first section examines visualization methods for incompressible flows, emphasizing the quantitative developments of both low and high concentration tracer techniques. More recent applications of both digital image processing and analysis to visualized flows are then reviewed with emphasis again being turned to the quantitative initiatives of past researchers. The latter section of Chapter Two examines various aspects of bluff body aerodynamics with particular attention being drawn to the vortex street and other flow details that may be of immediate relevance to the comparative studies and physical implementation of the digital imaging technique. Examples of such details include aspects of entrainment, vortex shedding, base-bleed and the influence of splitter-plates.

Chapter Three provides a general introduction to the subject of digital imaging and real-time image analysis. Readers who are completely conversant with all aspects of real-time video digitisation and analysis may, if desired, pass over the first two sections of this chapter and turn directly to section 3.4, which describes the imaging facilities used for this particular study. For those Readers not familiar with digital imaging, the first section of this chapter introduces various forms of image sensor such as still cameras, cinematography and videography. The following section then continues to describe the fundamental aspects of digital image acquisition, display, storage and analysis,
with particular emphasis being placed on the constraints imposed by real-time (continuous) image analysis. The final section of Chapter Three details the imaging facilities adopted by the present investigation, the digital imaging hardware modules and solid state video device.

Chapter Four provides details of the apparatus used in the experimental investigations involved in this dissertation. The first section describes the smoke tunnel facility and the larger boundary layer wind tunnel, both facilities being located in the Department of Civil Engineering. The subsequent sections describe the flat plate model, the pressure measuring and hot-wire equipment, with details being given of the environmental temperature fluctuation complications associated with the operation of hot-wire sensors within the smoke tunnel facility. The final section of Chapter Four examines the flow visualization equipment, with particular reference to the smoke generation, introduction method, optical sampling region size, camera lens and image sensor sensitivity.

Details of the experimental measurements undertaken are presented in Chapter Five, these being divided into two sections, the first describing preliminary measurements, the second outlining the comparative undertakings. The preliminary investigations were conducted in order to establish the basic flow properties associated with the flat plate model these being surface pressure measurements, spanwise spatial correlations, centreline static pressure distribution, mean velocities and turbulence intensities. The comparative wake measurements include intermittency, auto- and spatial correlations, wake interface statistics and mean fluctuating quantities.

Chapter Seven explores further the use of the digital imaging technique through alternative flow model investigations and reveals details of other visualization studies conducted by the Author which have been enhanced through the implementation of digital imaging concepts. The
first section, therefore, outlines some of the basic image processing algorithms and techniques used to enhance the presented flow visualization images. The following two sections investigate secondary vortices and a jet issuing into a crossflow, respectively, the quantitative digital imaging technique being applied in both cases. The next two sections are examples of further smoke visualization experiments in which digital image enhancement has been applied, these being boundary layer modification by passive means and dynamic stall on an aerofoil. The final two sections present examples of visualizations conducted by other research establishments that could be assisted by a digital imaging approach, these sections being involved with high-speed flow vapour-screen visualization and the implementation of shear stress sensitive liquid crystals. The latter shear stress/liquid crystal investigation provides an opportunity to use real-colour video digitisation rather than a simpler, intensity-based monochromatic video system, used throughout this dissertation.

Finally, the conclusions arising from the results of this thesis are discussed in Chapter Eight. This concluding chapter also outlines the overall concept behind the analysis techniques presented in this thesis and gives suggestions for further work in this field.
1.4 Summary

This chapter has highlighted the importance of flow visualization to fluid mechanics research and has indicated the possible benefits associated with the development of a quantitative flow visualization procedure, referred to as the digital imaging technique. In addition, the scope of the present work has been described, the investigations involving detailed comparative studies of a two-dimensional, flat plate wake and further studies on alternative two- and three-dimensional flow models. Digital imaging application examples, not directly applying the digital imaging technique are also reviewed. Finally, the organisation of this thesis has been outlined, together with brief details of the main topics covered by each chapter.

The next chapter is a review of the relevant existing literature with respect to both the flow visualization and comparative model aspects of this study.
CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

The present study is concerned with the exploitation of flow visualization techniques as a quantitative investigative tool. It has been appreciated for many years that flow visualization enables the qualitative examination of global flowfields, and that without such visualizations, it would be almost impossible to fully appreciate the results of single-location intrusive investigative probes. Following the recent technological advances in the quantification of continuous images, it would seem appropriate to examine the possibility of extracting useful quantitative data from flow visualization experiments. In particular, detailed flow data of a global nature would be extremely useful in the study of complex flowfields, where perhaps, the results obtained from traditional probes are most difficult to comprehend. The possible benefits of a quantitative flow visualization technique would, therefore, appear ideally suited to the study of turbulent flow mechanisms. This literature review undertakes a survey of previously established quantitative flow visualization techniques and examines a typical flow case which may be used for the purpose of comparative experimental studies. The review sections of this chapter are as follows:

2.2 Flow Visualization Techniques

2.3 Bluff Bodies and Vortex Streets

Section 2.2 of this review surveys the broad spectrum of flow visualization techniques available to fluid dynamicists and reviews their applicability to quantitative turbulent flow analysis. The section first examines optical flow visualization, outlining details pertinent to shadowgraph, Schlieren and interferometry investigations.
The review also develops the examination of visualization techniques to include seeding methods which use passive contaminants. Having established their capabilities and limitations, previous attempts to quantify these types of flow visualization images are examined, indicating the relative achievements of such methods to-date.

Aerodynamic and hydrodynamic flow visualization experiments since the last century have been undertaken into numerous flow configurations using a multitude of models and techniques. Classical examples of flow visualization have illustrated the flow around a bullet, shock waves during supersonic flight and transition to turbulence in pipe flows. The present study is, however, principally concerned with the investigation of turbulent flows. In particular, it is necessary to compare the results of a quantitative flow visualization technique with the established experimental results of a well-documented, yet reasonably uncomplicated, turbulent flow regime. In order to produce a basis for such a comparative study section 2.3 examines the literature associated with two-dimensional bluff body flows, with particular reference to a thin, sharp-edged flat plate model. The investigative knowledge associated with the vortex street which occurs behind bluff bodies is summarised and includes theoretical as well as experimental research undertakings. The flow characteristics of a simple two-dimensional model may be affected by various factors whose influences must be appreciated in order to allow justifiable comparisons between different models of similar geometry. The flow characteristics of a two-dimensional flat plate model may, for instance, be influenced by three-dimensional effects induced by model/wall interactions. With respect to this effect the section examines the influence of:

(i) model aspect ratio, and

(ii) use of model end-plates.
An examination of a wake flow using a visualization technique such as smoke flow visualization may be undertaken indirectly, by studying the motion of smoke originating from the freestream flow, or directly, by observing the motions of smoke placed immediately into the wake region. The latter method would appear to be best suited to the quantification of turbulent flow characteristics, as the seeding medium is restricted to, and influenced by, the turbulent flow motions. Direct wake visualization seeding does, however, require the 'injecting' of a passive contaminant into the near-base region of a model. In the case of a flat plate model, smoke injection can be achieved through a small-bore tube placed immediately against the model's rear face. The sketch below indicates the physical configuration of such a wake flow visualization injection tube.

The review examines the literature in order to analyse the possible influences that may be caused by the incorporation of such a smoke injection arrangement from the aspects of:

(i) introduction of base-bleed into the wake, and

(ii) after-body or splitter plate effects.

Finally, the difficulties of using a discriminator, such as the fluctuations in velocity signals, to detect turbulent or non-turbulent flow regions are surveyed. The basic velocity signal discriminatory techniques (which have led to the determination of the majority of intermittency functions) are expanded to examine the use of passive scalars, such as heat or smoke, as alternative turbulence detectors.
2.2 Flow Visualization Techniques

The importance of flow visualization techniques as a qualitative flow mechanism indicator is widely accepted in the realm of fluid mechanics. Indeed, on many occasions a global view of a complex flow pattern is an essential prerequisite to its understanding. The first sketches of vortical motion were produced during the fifteenth century by Leonardo da Vinci (1923, reproduced). These few sketches allowed him to postulate anatomical theories concerning the flow of blood inside the aortic heart valve. During the last century of visual experimentation, flow visualization techniques have developed from an art into a complex science, capable of yielding quantitative flow data. Whilst the discussions within this chapter will review wind tunnel based visualization techniques it is, of course, possible to conduct certain full-scale visualization experiments, a recent overview of which was produced by Crowder (1986).

Readers wishing to discover the many different facets of flow visualization are recommended to the Proceedings of the International Symposia on Flow Visualization which have been held in Tokyo (1977), Bochum (1980), Michigan (1983) and Paris (1986).

Flow visualization techniques may be coarsely divided into two major categories:

2.2.1 optical flow techniques, or
2.2.2 passive contaminant techniques.

Optical flow visualization reveals density or refractive index variations, whilst seeded flow visualization generally marks a fluid with tracer particles such as dye or smoke. Although these two categories may normally be regarded as mutually exclusive, it is essential to examine the merits of both categories with regard to the establishment of a quantitative flow visualization technique.
The following review section will survey both afore­
mentioned types of flow visualization with respect to their
quantitative capabilities and their applicability to various
flow regimes. Where appropriate, previous quantitative
analyses of visualization images are included and their
appropriate individual details discussed.

2.2.1 Optical Flow Techniques

Quantitative flow data may be extracted directly from a
number of optical flow visualization techniques. Such
techniques may be regarded as 'absolutely non-intrusive',
providing visualizations of density variations within a flow
regime without physically interfering with the flow. Due to
its nature, optical visualization is most widely used for
compressible flows and heat or mass transfer experiments,
although stratified fluids and mixing flows may also be
studied. An historical and experimental overview of most
modern optical flow visualization techniques has been
provided by Merzkirch (1974). The three basic optical
methods may be regarded as:

(i) Shadowgraph technique,
(ii) Schlieren method, and
(iii) Interferometry.

The quantitative analysing capability of these methods is
associated with their sensitivity to density variations:

(i) Shadowgraph - changes in refractive index,
i.e. second-order derivative density changes,
expressed as $dn^2/dy$.
(ii) Schlieren - first-order derivative density
variations, expressed as $dn/dy$.
(iii) Interferometry - absolute density changes,
expressed as $\Delta n$.

The following section will survey the above-listed methods
to examine their applicability to quantitative analysis.
(i) Shadowgraph

The shadowgraph technique is widely regarded as providing purely qualitative flow information, but has been successfully utilised by Schapker (1966) to provide basic statistics of high-speed turbulent wake boundaries. In his study, shadowgraph outlines of three cone and three sphere wakes were analysed to provide statistical information regarding the wake interface motion. Outlines were recorded manually providing, on average, 500 points per image. The interface information gathered in this manner represented a total of 40,000 points for the entire study. Schapker concluded that the probability distribution of the wake interface was similar to the Gaussian distribution reported by Corrsin and Kistler (1955) for low-speed flow boundaries. More recently, Herman and Jimenez (1982) presented a computer analysis of the plane mixing layer, through a quantitative investigation of a high-speed shadowgraph film. The mixing layer was established between two streams (mean velocities 10.0 m/s and 3.8 m/s) of Helium and Argon. The shadowgraph film was digitally analysed to measure the concentration of eddies and to examine the time-history of their evolution. This study was undertaken on a large mainframe computer facility but due to its complex nature was only capable of analysing 373 frames of flow information. (A more detailed account of the influence of digital image processing is undertaken later in this review).

The shadowgraph technique, although optically simple, does not provide direct quantitative data. The statistical data reviewed above has merely inferred flow characteristics from the motion of shadowgraph outlines and does not provide a means for accurate quantitative analysis.

(ii) Schlieren

The Schlieren method is probably the most frequently applied optical visualization system in aero- and thermo-dynamic laboratories. Although it combines a relatively
simple optical arrangement with a high degree of resolution, it too may be regarded as a qualitative flow characteristic indicator. Many examples of excellent Schlieren visualization are to be found in the previously mentioned International Symposia on Flow Visualization.

(iii) Interferometry

The Mach-Zehnder interferometer provides direct density measuring capabilities and has attracted the greatest attention amongst optical techniques in recent years. As a development from standard interferometric analyses of compressible flows, such as the density fluctuations in hypersonic turbulent wakes by Lien and Eckerman (1966), holographic interferometry now represents the 'state of the art' in optical flow visualization. An excellent introduction to holographic interferometry with application examples in aerodynamics and heat and mass transfer measurements was provided by Vest (1979). Some of the benefits of holographic interferometry are:

(i) the cancellation of phase errors produced by low-quality optical elements,

(ii) the capability of using transparent models to obtain corner-flow data, and

(iii) the ability to reconstruct several interferograms with different viewing angles from one single hologram.

Lauterborn and Vogel (1984) have reviewed modern optical techniques in fluid mechanics, emphasizing some of the advantages of holographic flow visualization and holographic interferometry.

Comparative two-dimensional transonic flow studies between holographic interferometry and traditional surface pressure measurements were conducted by Bachalo and Houser (1985). In their study two aerofoil sections were tested over a transonic Mach number range of 0.3 to 0.9, and the agreement between surface pressure and holographically inferred
pressure was found to be good. They also introduced a real-time holographic interferometer system and expressed the desire for a real-time quantitative analysis procedure. A similar desire was echoed by Settles (1986a) who declared that the promise of holographic flow visualization had been realised only partially because the problem of data reduction was proving too complex for many applications. Whilst many authors have demonstrated the feasibility of quantitative data analysis, few have been able to achieve it. The major problems of data reduction were outlined in detail by Trolinger (1985). In an attempt to explain why a considerable degree of image pre-processing must be undertaken on interferogram images before the task of fringe position or phase difference measurement may be undertaken, Trolinger identified a few physical characteristics of a typical interferogram. These characteristics include:

(i) broken fringes,
(ii) variable image contrast,
(iii) extraneous fringes,
(iv) diffraction noise,
(v) closely spaced fringes, and
(vi) background noise.

Image pre-processing was used to overcome the above-listed interferogram characteristics by Boyd et al (1985), and Hunter and Collins (1986). Boyd et al introduced an automatic interferometric analysis technique which was used to investigate natural convection in a horizontal annulus. Hunter and Collins produced both double-exposure and real-time holographic interferograms to study heat transfer from a heated surface under forced convection. They found manual data extraction very tedious and developed an automatic analysis procedure. The analysis consisted of digital image pre-processing and data analysis algorithms which were operator controlled and directed at all stages, rather than being part of an automated 'production line' type system.
These two latter examples illustrate how digital imaging may be utilised in the data reduction of interferogram images. However, without the facilities of a high resolution digital imaging processor capable of complex image manipulation, many researchers may be forced to adopt the subjective judgements of a human operator and employ a simple digitising tablet to quantify their interferometric images.

In addition to the highly complex nature of interferograms, all optical flow visualization techniques integrate the density information along the optical path of the illuminating source. Standard interferogram results, for instance, provide an instantaneous mean pressure value integrated over the width of the test flow, whereas direct surface pressure measurements provide time-averaged mean pressure values at single locations on a model. Localised pressure fluctuations or flow structures may, therefore, be undetectable using optical flow visualization techniques and direct comparison of experimental data must be tentatively undertaken. Further, in order to obtain three-dimensional flow characteristics, multiple viewing angles of the flow must be studied. Zien et al (1975) successfully applied holographic interferometry to a large-scale three-dimensional density field experiment in a wind tunnel. The experimental arrangement was extremely complex and would not have been achievable in most testing facilities. Whilst such a method would be convenient for steady flows, it would be essential for transient flows. In relation to this point, a three-dimensional, transonic flow has been studied by Snyder and Hesselink (1984) at NASA Ames. Holographic interferometry was used to study the flow around a revolving helicopter blade. It was found that 40 independent views at 2 degree intervals were sufficient to reconstruct the flowfield.

A later publication by Snyder and Hesselink (1985) outlined in more detail their three-dimensional reconstruction technique which was called optical computer assisted tomography (OCAT). It was reported that the full
implementation of a tomographic system was proposed for a future investigation of a time-varying three-dimensional combusting flow.

In addition to the above-mentioned data reduction complexities, certain physical flow attributes are also necessary to facilitate the use of optical methods. Principally, optical flow visualization requires detectable changes in fluid density in order to produce good quality results. Wind tunnel flows of less than Mach 0.2, for instance, have too low a kinetic energy to produce sufficient density changes unless external energy in the form of heat may be added to make the flow compressible. Density changes can also be achieved in stratified water flows, which provide a means to study low-speed fluid mechanics phenomena. This was demonstrated by Debler and Vest (1977) who produced a holographic interferogram of a rectangular cylinder moving slowly through density-stratified salt water. Excellent results were achieved though the visualizations were through the walls of an ordinary plate glass tank. Despite alleviating the requirement of a transonic wind tunnel, water tank experiments are incapable of reproducing the Reynolds numbers necessary to model most turbulent flow applications. In addition to density variation considerations, it must also be noted that the development of an optical flow visualization system requires the provision of a high-power laser, accurate laser and imaging optics, and vibration-free mounting assemblies and test environment. Consequently, the cost of such equipment is extremely prohibitive, restricting its use to a few well-appointed research establishments.

The preceding review of optical flow visualization techniques has demonstrated that much effort is currently being devoted to obtaining quantitative flow information from interferometric techniques.
Quantitative optical flow visualization is, however, restricted by the following characteristics:

(a) Detectable variations in fluid density are required. Typical examples being compressible, stratified or mixing flows.

(b) Vibration-free operating environment such as high-precision optical beds.

(c) Density changes are integrated along the entire optical path which is normally across the width of the flow indicating that accurate single-view visualizations will only be produced for two-dimensional flows.

(d) Three-dimensional flows require simultaneous multiple-viewing visualizations and analysis of the subsequent data is highly complex.

(e) Data reduction of visualized interferograms is complicated and requires image pre-processing.

(f) Transient flows require a real-time system which when combined with (d) and (e) indicates the full complexity of real-time automatic data reduction.

The above characteristics serve to indicate that although optical flow visualization methods may be invaluable to specific flow conditions such as transonic wind tunnel studies, their use is limited and requires highly complex experimental and analytical facilities. The majority of experimental aerodynamics research facilities are low-speed wind tunnels which are generally restricted to the study of incompressible flows.

Flow visualization techniques for incompressible, low-speed flows incorporate the use of low or high concentrations of tracer particles which when acted on by the flow indicate indirectly, the flow motion.

The following section of this review will examine quantitative flow visualization techniques with respect to the analysis of incompressible turbulent flows.
2.2.2 Passive Contaminant Techniques

The majority of the techniques discussed in the following section incorporate image processing techniques, such as digital image processing and analysis. The following review details assume only a basic knowledge of digital image concepts and does not involve in-depth analysis of digital image processing techniques or algorithms. Readers who have no basic knowledge of image processing are recommended to the publication of Pratt (1978) which provides an excellent introduction to this subject.

The very wide range of flow visualization techniques available for the study of incompressible flows dictates that the following discussion be limited to consider only specific visualizing techniques. The scope of this review has, therefore, been restricted to the examination of tracer methods with most attention being paid to visualization techniques involving the use of smoke particles in wind tunnels. The primary objective of this review is to analyse the quantitative capabilities of various visualizing techniques, with specific reference being paid to their applicability to the study of turbulent flows. The visualizing techniques reviewed may be coarsely divided into the following categories:

(i) Visualization as a qualitative aid to the analysis of probe data,

(ii) Point concentration measurements in visualized flows,

(iii) Quantitative analysis of sparsely-seeded visualizations,

(iv) Quantitative analysis of highly-seeded visualizations.

The following review section will examine the above-listed categories commencing with a brief survey of flow visualization used as a qualitative aid to the analysis of traditional probe data.
(i) Quantitative Analysis Aid

A short review paper which examined attempts aimed at combining flow visualization with quantitative hot-wire anemometry has been produced by Freymuth et al (1983). In an earlier publication, Freymuth (1966) had demonstrated that visualized vorticity patterns in a free shear layer during forced convection could be correlated with hot-wire signatures. No direct quantitative data was achieved from the visualizations, but theoretical misinterpretation of the hot-wire data was successfully avoided. Freymuth et al appeared unimaginative in their attitude toward quantitative flow visualization and adopted a traditionalist view of a qualitative technique which may at best inspire concepts or reinforce anemometer data. In reality, the quantitative determination of statistical flow details obtained directly from visualized flows had been reported in the early sixties.

(ii) Point Concentration Measurements

Rosensweig et al (1961) devised a visual method of measuring concentration fluctuations and Falco (1980) combined smoke flow visualization and traditional hot-wire anemometry in a study of turbulent boundary layers. The flow was visualized using an oil-fog contaminant and a 10 Watt Argon-Ion laser sheet illumination source. Three-dimensional features were studied by simultaneously viewing two mutually orthogonal light sheets which intersected at some desired location within the flowfield. In addition, hot-wire and visual data were simultaneously obtained by digitising 8 velocity probe outputs at a rate of 10 kHz (each with 12-bit resolution) and filming using high-speed cinematography at a rate of 500 frames per second. This experimental combination provided ten seconds of flow data expending 100 feet of photographic film and filling 1.6 megabytes of disk storage. The hot-wires were operated within the smoke-filled flow regions and the results indicated that the hot-wire calibration errors caused by the presence of the oil-fog
were relatively small. Falco also conducted an experiment to examine the location of the turbulent/non-turbulent interface, as simultaneously indicated by a hot-wire and visually observed as the smoke/no-smoke boundary. Although inconclusive, the results obtained verified that the smoke/no-smoke boundary was highly correlated with the turbulent/non-turbulent interface. The significant reason for Falco's inability to be more conclusive with regard to this point was the uncertainties involved in turbulence detection using hot-wire velocity signals. This point is discussed further at a later stage of this review (see section 2.3), where the determination of the intermittency function is surveyed.

One of the first quantitative analyses of turbulent flows was conducted by Rosensweig et al (1961) who devised a visual method of measuring point concentration fluctuations. A system undergoing turbulent mixing was visualized using a passive smoke contaminant and was termed the smoke-scattered light technique. A sketch of the experimental arrangement is shown below.

A turbulent seeded jet was illuminated by an intense focussed beam of light (1/16 inch or 1.59mm in diameter). It was assumed that the smoke particles scattered light in proportion to their concentration at the illuminated point. The output of the phototube was then considered to be directly proportional to the instantaneous smoke concentration of the source-field.
Experimental measurements were conducted for jet nozzle velocities of 100 ft/sec (approx. 30.5 m/sec, Reynolds number $2.62 \times 10^4$ based on nozzle diameter). Concentration profiles, fluctuation spectrums, correlation coefficients and integral scales were presented. Correlation measurements were performed by focusing the light from two illuminated spots onto a single phototube, and correlating the phototube outputs from both spots with the outputs from the individual spots examined separately.

In a later publication Becker et al (1967a) used an improved phototube to study a smoke jet having a nozzle air velocity of 122 m/sec. In addition to the fluctuating quantities previously mentioned, this latter study also analysed the intermittency factor. Becker et al (1967b) examined an isothermal, turbulent, axisymmetric air/air free jet with the nozzle flow again marked by an oil smoke. Mean concentration, intensity of concentration fluctuations, integral length scales and correlation coefficients were found to compare well with previously published data. However, comparable intermittency results obtained by Corrsin and Kistler (1955) were found to be ten percent smaller than those obtained using the phototube technique. Becker et al noted that the light-scatter technique discriminator for detecting intermittency rested on a sharply defined and experimentally uncomplicated procedure, whereas the detection of intermittency through velocity fluctuations was inherently more nebulous and experimentally difficult. A similar observation was reported by Fiedler and Head (1966). The response of the phototube used for Becker et al's latter studies was linear with light flux up to a repetition rate of approximately 100 MHz. This high sampling rate allowed marker concentration fluctuations to be achieved up to an experimental limit of 40 kHz. Higher frequencies were undetectable due to electronic noise levels and control volume size. The technique was, however, limited by the single-point nature of its operation, and to-date no further references to this specific light-scatter technique have been encountered. It is perhaps surprising that the
authors did not propose an idealised improvement to their system by envisaging a two-dimensional illumination sheet being sensed by an array matrix of phototube sensors.

Fiedler and Head (1966) presented a method of intermittency measurement in a turbulent boundary layer which also incorporated a photo-electric probe. They developed the photo-probe technique in order to corroborate intermittency results obtained by their improved version of Corrsin and Kistler's hot-wire intermittency detection method. The so-called 'photo-electric' method focussed a phototube on an illuminated cross-section of a smoke-filled boundary layer. The output from the phototube was used as a simple 'on-off' turbulence detector. The success of the photo-probe method obviously depended upon the smoke being effectively confined to the turbulent regions of the flow. This would seem to be the case, since smoke particles, if they are sufficiently small, can only be transferred to the outer, irrotational flow by molecular action, whilst being freely dispersed within the flow by turbulent motions. Direct comparisons of both the photo-probe and hot-wire signals at almost the same location, as well as comparisons of the intermittency factor obtained from both detection circuits led Fiedler and Head to conclude that smoke could be successfully used as a discriminator between turbulent and non-turbulent flow.

Murlis et al (1982) also noted that smoke cannot migrate further than the inner edge of the viscous superlayer. They suggested that the smoke/no-smoke interface does not, therefore, correspond exactly to the turbulent/non-turbulent interface. This physical difficulty led them to propose that the deep and narrow boundary layer structure fissures present in smoke visualizations, although free of smoke could, in fact, contain significant vorticity and would, therefore, be detected as turbulence by probe measurements. Fiedler and Head, however, felt obliged to place more confidence in their photo-probe results than the hot-wire data, suggesting that the photo-probe could distinguish narrow regions of smoke-free fluid where the hot-wire
recorded a velocity fluctuation indistinguishable from turbulence. Conditional, hot-wire sampling results achieved by Murlis et al also implied the presence of large, deep fissures similar to those observed on smoke photographs, indicating real intrusions of irrotational fluid into the turbulent region. Unlike the previously outlined light-scatter method described by Rosensweig et al and Becker et al, Fiedler and Head limited the photo-electric method to intermittency detection only. They made no attempt at further statistical analysis of the phototube output, nor did they consider attempting correlation techniques. Once again it would seem plausible that the lack of further reference to this technique may have been due to its single-point nature of operation, and not due to any major uncertainties in the results obtained.

(iii) Sparsely-Seeded Visualizations

In addition to flow visualization experiments involving the use of single-location phototube probes such as those previously reviewed, attempts have also been made to obtain global quantitative data from visualization techniques using low concentrations of tracer particles. The deviation of individual tracer particle's pathlines from those of a fluid has been a source of theoretical and experimental investigation. Although not discussed further in this review an interesting survey of associated articles was produced by Somerscales (1971).

An excellent example of the quantitative particle pathline analysis is the publication of Wood (1967) who studied an incompressible wake flow. His study was inspired by the desire for the detailed examination of the wake vortex structure as influenced by base-bleed. Although Wood conducted his study in a water tank, his analytical procedure could have applied equally well to a wind tunnel investigation using smoke particles. The flow was made visible by a suspension of 0.2mm diameter polystyrene beads which were pre-wetted in dilute detergent and when evenly
distributed over the flow surface, sank slowly as a uniform cloud. The local flow velocities were determined by examination of the length of the particle streaks, with respect to the scale of the photograph and the exposure time (approximately 0.13 seconds). Accurate illumination periods were accomplished by the incorporation of a mercury vapour lamp which flashed one hundred times per second. The streak lengths were measured using a travelling microscope, leading to a laborious and tedious data collection process.

Although Wood's (1967) analysis of local velocities and trajectories disregards the possibility of errors due to three-dimensional wake effects (undoubtedly present even when considering a nominally two-dimensional model) his conclusions with regard to the vortex formation process, spacing and strength were revealing.

Recent advances in digital computing initially facilitated the replacement of the travelling microscope, as used by Wood (1967), by a personal computer digitising tablet, as employed by Imaichi and Ohmi (1983) for the study of a two-dimensional vortex flow. Two to four thousand local velocities could be extracted from each streakline photograph, although this procedure still required up to four hours of operator-controlled digitisation. The advent of digital image processing has allowed the automated analysis of seeded flows, examples of which were outlined by Schon (1984, 1986) and Kobayashi et al (1986). The methods described incorporated digital image processing routines to clarify and simplify the visualized images before performing velocity analysis routines on the enhanced images. A recent paper by Hentschel and Stoffrengen (1986) illustrates how particle image velocimetry may be applied to complex flows.

The useful application of seeded flows to determine velocity fields depends primarily on the correlation of the seeded particle pathlines with local velocity components. Such techniques may ideally be applied to low velocity two-dimensional flows, the study of turbulent three-dimensional
regimes adding considerably to the experimental difficulties and inaccuracies involved. The minimum requirement for the analysis of highly turbulent flows is that the statistical characteristics be examined over a large population sample. The more involved the data extraction from individual images becomes, the more difficult it is to consider large populations, and the less useful such techniques are to turbulent flow studies. Borleteau (1984, 1986) demonstrated that by reducing the volume of data to be analysed, large numbers of images may be automatically analysed. A plane mixing layer was visualized by a single smoke filament, three-dimensional effects' being enhanced by a light sheet coinciding with a plane normal to the freestream. Three to four thousand recorded images were automatically digitised and analysed to examine the successive positions of light spots (the results of which are sketched below). Although described as automated, this simple technique was not capable of direct on-line video data analysis, although the Author would tentatively suggest that further development using two semi-cylindrical lens/linear CCD array combinations could conceivably accomplish on-line analysis at equivalent (or higher) framing rates.

Although quite simplistic in principle, the Borleteau filament visualization allows the analysis of significantly large sample populations, rather than being restricted to few images containing detailed information, such as the previously outlined method of Imaichi and Ohmi (1983).
Smoke-filament experiments are not applicable to turbulent visualizations due to the highly dispersive nature of the flow, and having reviewed alternative quantitative visualizing techniques, the predominantly suitable incompressible turbulent flow visualizing technique would appear to be that of smoke flow visualization using high seeding particle concentrations.

(iv) Highly-Seeded Visualizations

Smoke flow visualization and digital image processing may be used purely as an image enhancement technique to highlight certain features of a visualized process. This approach is widely used and although not providing quantitative data may enable a clearer comprehension of a particular event. An example of the use of digital image processing in this manner is the work of Wallace and Balint (1985) who visualized turbulent boundary layers to study the effects of different types of boundary layer trip. Gradient and base relief algorithms were performed on digitised images to highlight the spatial light intensity gradients and to accentuate internal structures respectively. Whilst revealing image structures that may otherwise not be visible, the use of digital image processing enhancement routines does not provide direct quantitative data.

Examples of more quantitative digital image processing applications will now be reviewed. Classical laser sheet visualization has been combined with digital imaging correlation techniques by Beauvoit et al (1986) to determine the convection velocities of typical large-scale visualization events. In their study the unsteady mixing of cold air with seeded hot air was visualized using a 3 Watt Argon-Ion laser sheet. The pictures were digitised using a photodensitometer to produce a digital image having a spatial resolution of 512 * 512 picture elements (pixels). The images were enhanced before determining their cross-correlation factors, or studying the displacement of the
visualized interface to reveal local structure velocities and record their shape evolution. The method, as reported, was extremely limited due to the consideration of only two visualized frames, but the principle of image correlation and interface displacement analysis would appear to be applicable to many flow regimes, including turbulent flows.

Flow visualization allows the simultaneous examination of entire flowfields. In this respect, it provides a unique experimental facility to examine the temporal development of large flow volumes. In particular, it would seem an excellent tool with which to monitor mass dispersion, both in water and air. Arnold and Haenscheid (1984) described an investigation of two-dimensional mixing processes in an open water channel flow which used digital image analysis to provide experimental data for the prediction of river pollutant dispersion. Schon (1984) and Ohba et al (1984) were able to analyse gas diffusion patterns in a wind tunnel in a similar manner. Schon visualized smoke flow patterns using a 5 Watt Argon laser, projected into a light sheet by a rotating, multi-faceted mirror system. The images were recorded in either a still frame format or by a ciné camera and subsequently digitised to produce a 512 * 640 picture element image (8-bit grey levels). Ohba et al used a similar digitisation system and both studies examined time-averaged statistical data for the diffusion of wind tunnel stack emissions. Ohba et al's experimental arrangement is shown below.
Diffusion patterns at different times were studied, mean concentration and root-mean-square concentration values being inferred from the image intensities over a specified period. Further details of Schon's experiments were presented by Balint et al (1985). Ohba et al's results were compared to an established gas sampling method and were found to agree well except at locations close to the terrain surface where reflections caused inaccuracies in the digital imaging results. Schon extended his study to include an analysis of the concentration field of a turbulent round jet (exit velocity 5.0 m/s, corresponding to a Reynolds number of 10,000). A set of 310 selected images were analysed to produce mean concentration and root-mean-square statistics. Spatial correlations were also computed and the identification of alternate regions of positive and negative correlation indicated the presence of large-scale structures. Although Schon's statistics must be limited to an indicative trend analysis due to the small sample population, analyses of this nature would appear to offer far greater experimental efficiency than is available with single-location probes. However, studies of turbulent flows require the analysis of substantial sample sizes to provide accurate time-averaged data and the systems described above would not seem able to accommodate such large populations.

Keffer et al (1985) described an image processing technique which examined up to 3600 visualized images from pre-recorded films. The films studied consisted of a simple round jet and the complex wake of two unequal diameter, closely spaced cylinders. They were able to examine 3600 frames of the jet flow and 1000 frames of the cylinder arrangement. The analysis consisted of determining the location of the turbulent/non-turbulent interface at various downstream locations, as indicated by the smoke/no-smoke boundary. A Bausch and Lomb image analysis system digitised the images via a densitometer for post-processing by IBM 3033 computer. Having analysed the digitised images, the mean location and variance of the interface at various downstream locations were presented for both cases. Further
probability moments, burst rate and correlation statistics from the same studies were reported by Shokr et al (1983). The interface statistics reported in these studies were quite unique in nature and could not have been achieved using traditional anemometry equipment. The analysis was, however, complicated by the need to analyse pre-recorded images, which in turn led to a time-consuming analysis procedure and restricted the size of the possible sample populations. It would seem a natural progression to develop this analysis procedure to provide an on-line or real-time image analysis technique.

Keffer et al (1986) combined a digital edge detection algorithm with clustering routines to provide edge delinearation and coherent structure recognition for a turbulent wake flow. Gennero and Mathe (1985) also reported the real-time extraction of edges to study vortices. They visualized an aerodynamic wake (no precise details were given) using steam and digitised the output from a colour video camera (or video tape recorder) in real-time. The images had a spatial resolution of 280 * 192 pixels and 1-bit in grey-scale resolution providing a binary image of either black or white. The detected vortex edges were used to establish correlations between different geometrical parameters. The real-time binary video digitiser described by Gennero and Mathe would appear to be identical to the Computech digitiser board briefly described in a recent paper by Toy and Wisby (1986). Finally, although not performed in real-time, Kimura and Takamori (1986) have used digital correlation algorithms to study the flow around a circular cylinder model.

Recent advances in video digitising technology have far exceeded the low resolution binary digitiser used by Gennero and Mathe (1985). It is now possible to digitise (8 MHz flash analogue to digital converters) a medium resolution image (512 * 512 pixels) with 256 grey levels in real-time, with 40 MHz converters becoming more commonplace in higher resolution facilities (1024 * 1024 pixels).
The possibility therefore exists to extract useful flow data, such as that produced by Keffer et al (1985) and Shokr et al (1983), under real-time constraints. This would appear to provide the opportunity for an on-line digital imaging technique which could extract global data from flow visualization images. Furthermore, on-line analyses of video images would provide instantaneous global flow results and could be capable of considering large sample populations without the necessity for film developing or replay facilities.

The preceding section of this review has examined incompressible flow visualization with regard to obtaining quantitative flow data. It has been shown that low concentrations of tracer particles may be visualized and successfully used to measure local flow velocities. Such techniques are best suited to low flow velocities such as those found in water studies and become extremely difficult to analyse in three-dimensional turbulent flows. Traditional smoke flow visualization using high tracer concentrations has, in the past, been successfully analysed to produce concentration measurements associated with both turbulent flows and gas diffusion studies. To-date, few comparable results have been obtained and the statistics presented have generally examined small sample populations. If improvements to such techniques could be made, the possibility exists to observe entire flowfields simultaneously and to reduce the experimental time requirements presently associated with intrusive single-location probes.

2.3 Bluff Bodies and Vortex Streets

In order to determine the experimental characteristics of a proposed quantitative flow visualization technique, it is necessary to undertake comparative tests on a simple, yet 'interesting' flow model. The principal aim of this study is to apply a quantitative visualization technique to turbulent flows.
A well-documented yet challenging example of a turbulent flow is that associated with two-dimensional bluff bodies, of which the most fundamental is the flow around a two-dimensional, thin, sharp-edged flat plate. The principal flow characteristics associated with a flat plate model at moderate Reynolds numbers are:

(i) fixed flow separation points,
(ii) a strongly reversing vortex formation region, and
(iii) the alternative shedding of vortices to produce a von Karman vortex street wake structure.

These features are indicated in the following sketch of an instantaneous flat plate flow regime.

This review section introduces the theoretical background to flat plate flows and examines the similarity of all wake flows through the realization of a Universal Wake Strouhal number.

A feature common to all turbulent flows and in particular, to wake flows, is the process of entrainment. The various suggested entrainment hypotheses are surveyed and the importance of large-scale flow structures in this respect is highlighted. Experimental investigations of two-dimensional plate flows are then reviewed with particular reference to turbulent wake parameters. The following sub-sections
examine the above-outlined topics in detail, the individual subject titles being:

2.3.1 Theoretical Considerations
2.3.2 Universal Strouhal Number
2.3.3 Vortex Shedding
2.3.4 Entrainment
2.3.5 Experimental Considerations
2.3.6 Intermittency Detection

The latter review sections examine the experimental difficulties encountered when comparing models of similar geometry but different model parameters, including:

(i) length to breadth aspect ratio,
(ii) use of end-plates, and
(iii) blockage effects.

In addition, the difficulty of detecting the turbulent or non-turbulent state of a flow region is discussed with particular reference to the use of hot-wire velocity signals and passive scalars as turbulence discriminators.

The present study is only concerned with models placed in a uniform crossflow. The importance of sheared flow testing and the development of boundary layer simulations is appreciated, but has not been reviewed due to the lack of direct relevance to the present study. For those Readers interested in such flow configurations, Everitt (1982) studied the flow around a normal flat plate close to a large plane surface for a range of boundary layer thickness. Sakamoto and Arie (1983) examined a flat plate mounted on a smooth plane in a turbulent boundary layer and Sakamoto and Oiwake (1984) examined the fluctuating forces induced on a three-dimensional body placed vertically in a turbulent boundary layer. Mauk (1969) studied correlation and
shedding frequency results in a flat plate wake, both in uniform and sheared flow. Pulsed-wire studies were conducted by Bradbury and Moss (1975) under the same conditions, and the spanwise cellular nature of vortex shedding from a two-dimensional D-section cylinder in a sheared flow has been examined by Maull and Young (1973, 1974) and Griffin (1985).

2.3.1 Theoretical Considerations

The following paragraphs introduce the theoretical aspects of the flow around a flat plate model. One of the most important theoretical wake solutions was formulated by Roshko (1954a). Roshko allowed some vorticity annihilation in the free shear layers and was able to combine the free-streamline theory with the vortex street theory of von Karman to obtain a drag solution dependent on only one experimental measurement. Roshko's modified Kirchhoff theory was based on the hodograph, and called the notched-hodograph theory. The base pressure parameter, \( k \), (where \( C_{pb} = 1 - k^2 \)) was introduced and a Universal Strouhal Number \( St_* \) proposed, where \( St_* = f d' / U_b \). Roshko suggested that for a given body shape, the drag, \( C_D \), and wake width, \( d' \), are functions of the base pressure parameter, \( k \), only.

It was found that \( St_* = 0.16 \) for all cylinders. The wake Strouhal number may be related to the ordinary Strouhal number, \( St \), by

\[
St_* = \frac{St}{k} \left( \frac{d'}{d} \right)
\]

Roshko (1954b) highlighted the differences between a real and idealized vortex street. These differences being:

(i) the street is not infinite,

(ii) the vortex spacing ratio is not constant, and

(iii) real vortices have cores of finite radius which grow with downstream distance so that the vortices diffuse into each other and decrease in circulation.
Abernathy and Kronauer (1962) considered the non-linear interaction of two infinite vortex streets in an inviscid, incompressible fluid. Abernathy and Kronauer's pioneering work led to the development of the discrete-vortex method. In considering the growth of large amplitude disturbances, it was deduced that the broadening of vortex streets downstream in bluff body wakes was a direct consequence of the interaction of the vortex rows. Abernathy (1962) applied the free-streamline theory to the flow over an inclined plate and calculated the pressure distribution on the front surface of the plate at different angles of incidence to the freestream (found to correspond well to Fage and Johansen's (1927a) experimental measurements). The theory also predicted the locations of the free-streamlines and calculated traditional as well as modified Strouhal numbers.

Further improvements followed rapidly, and Sarpkaya (1975) applied the potential flow model to the vortex shedding behind an inclined flat plate. With the flat plate inclined between 40 and 80 degrees to the freestream, Sarpkaya calculated that the Strouhal number, St, was equal to 0.154. This compares well with the equivalent values obtained by Donoso et al (1983) who found St to be 0.153 at 90 degrees, Fage and Johansen (1927a) who found values of between 0.146 and 0.149 over the range 30 to 90 degrees and Hoole (1968) who quoted 0.145 for the same range. The experimental variability in blockage ratio, aspect ratio, end-effects and freestream turbulence intensity would appear to indicate that Sarpkaya's value of 0.154 was not significantly different from experimental results. Calculated normal-force coefficients were also found to be only 20 percent greater than the comparable results of Fage and Johansen. These results were, however, achieved without the introduction of an artificial reduction in the strength of shed vortices which would have reduced the normal-force coefficients.
2.3.2 Universal Strouhal Number

Calvert (1967) introduced a Universal Strouhal number in his measurements of the wake behind cones. The wake width was defined to be the measured transverse distance between the velocity fluctuation peaks, at the point of minimum pressure on the downstream wake centreline. The sketch below illustrates the wake width definition.

Simmons (1977) and Griffin (1978) adopted this definition of wake width in their Universal Strouhal numbers. The longitudinal position of the static pressure minimum from the model base was experimentally determined by Simmons. A minimum base pressure coefficient of approximately -2.1 at a distance of 1.27 D was recorded for a flat plate model, which agreed well with Hoole's (1968) distribution. The wake width at this location, as previously described, was found to be approximately 1.6 D.

The universal Strouhal number, \( St^* \), is defined as

\[
St^* = \frac{Nd'U}{U_0 d'Ub} = St \left( \frac{d'}{d} \right),
\]

where, \( N \) is the vortex shedding frequency, \( k \) is the base pressure parameter, and \( d' \) is the wake width.
Simmons found this universal Strouhal number to have a constant value of about 0.163. Griffin (1981) re-defined Calvert's universal Strouhal number, replacing the kU terms with the numerically equivalent value \( U_b \), where \( U_b \) is described as the mean velocity at the edge of the separated boundary layer. Griffin used this parameter to collapse the characteristics of a range of bluff bodies onto a single curve which is sketched below.

In considering universal wake similarity, Griffin (1981) demonstrated that the wake width for stationary and vibrating cylinders, as well as other two-dimensional bluff bodies, was correlated to the base pressure parameter, \( k \).

### 2.3.3 Vortex Shedding

There have been many publications on the subject of vortex shedding, amongst which Berger and Wille (1972) stands out as a comprehensive review of papers published before 1972. Vortex shedding has also been the topic of Euromech meetings which have been reported on by Mair and Mauil (1971) and Bearman and Graham (1980).

All experiments conducted within low-speed wind tunnel facilities must make Reynolds number assumptions in order to justify their applicability to full-scale situations. The thin, two-dimensional flat plate model is considered to be
Reynolds number independent, indicating that any results obtained could be applied to other flow speeds or scales. A similar Reynolds number independency has been recently demonstrated by Nakagawa (1987), who investigated Mach-number effects on the vortex shedding behind a square cylinder, over a Mach-number range of $0.1522 < M < 0.9049$, Reynolds number range $0.696 \times 10^5 < Re < 4.137 \times 10^5$. Regular periodic vortex shedding was detected irrespective of the formation of shock waves. In conjunction with the work of Okajima (1982), it was suggested that the Strouhal number of a square cylinder could be estimated to be $0.13$ over a Reynolds number range of $100$ to $3.4 \times 10^5$.

2.3.4 Entrainment

One of the most fundamental aspects of turbulent flows, and in particular, wake flows is the concept of entrainment. The following review section will attempt to summarise the existing (perhaps somewhat limited) knowledge of the entrainment process.

The first entrainment hypothesis was reportedly introduced by G.I. Taylor in an unpublished wartime report on the dynamics of hot gases rising in air. In its original form, this hypothesis stated that the mean inflow velocity across the turbulent interface could be assumed to be proportional to a characteristic velocity, usually the local time-averaged maximum mean velocity, or the mean velocity over the cross-section at the level of inflow.

For many years, entrainment rates were known to be influenced by the folding of the turbulence interface due to the action of wake eddies. Townsend (1956, 1966) considered interface folding to play a fundamental role in the entrainment process. Townsend (1966) stated that the interface advanced into the ambient flow by a process of vorticity diffusion and subsequent amplification of diffused vorticity by straining. Entrainment itself was believed to be the result of small-scale 'nibbling' across the
turbulence interface and the following hypothesis was proposed. The growth of large eddies caused rapid entrainment which increased the turbulence intensity of the eddies causing large eddy damping and a decrease in their intensity. Townsend proposed an entrainment constant for a self-preserving flow, defined by:

\[ \beta = \frac{U_0 + \frac{1}{2} U_m + \frac{1}{2} U_m \frac{\partial V_{0.5}}{\partial x}}{\frac{1}{2} U_m} \]

where \( U_m \) is the difference between the freestream velocity and the velocity at the centre of the flow,

\( U_0 \) is the velocity of the ambient fluid, and

\( V_{0.5} \) is the distance of the 0.5 intermittency factor from the flow centreline.

The value of the entrainment constant for a wake flow was found to be 0.4. Townsend (1970) developed a similar expression by considering the overall balances of momentum and total energy, stating that entrainment rates could be predicted to within ten percent for many free flows without a need to refer to entrainment mechanism details. Townsend also proposed that entrainment was a folding-in engulfment of the ambient fluid by interfacial movements. Bevilaqua and Lykoudis (1971) studied the mechanism of entrainment in a turbulent sphere wake using dyed fluid droplets. Papailou and Lykoudis (1974) suggested that a vortex draws in ambient fluid by the action of turbulent shearing forces. Part of the fluid is entrained by the vortex leading to its growth, whilst the remainder diffuses into the turbulent core through turbulence action. The mechanism was again inferred from flow visualization, and was thought of as a 'pumping' process. It was noted that the very rapid widening of the turbulent vortices in the near-wake region, indicated strong entrainment, and as the vortices moved downstream they diffuse by the action of turbulence, losing strength, and progressively slowing the entrainment rate.
The subject of entrainment and, in particular the entrainment mechanism has created great interest in recent years. Davies and Yule (1975) reported the proceedings of the Colloquium on Coherent Structures in Turbulence which involved itself with the discussion of entrainment. They noted that many presentations agreed with the view that the entrainment process involved engulfment, particularly by coalescing vortices, as opposed to a viscous 'nibbling' action at the outer turbulent region edge. Turner (1986) concluded that viscous diffusion of vorticity is important in the final digestion of ambient fluid into turbulent flow and the evolution of smaller-scale motions, but not in determining the overall entrainment rate.

Hussain (1986) intensively employed the coherent structure approach to turbulence study. He claimed that one inference from coherent structure interaction is that entrainment is not a 'nibbling' away of irrotational fluid at the turbulent/non-turbulent interface, but a result of large-scale ambient fluid engulfment due to the 'Biot-Savart' induction of large-scale coherent structures. Once the ambient fluid is entrapped within the influence of a coherent structure, the non-turbulent fluid is sheared into thin laminations so that molecular diffusion of vorticity by viscosity can effectively complete the turbulent entrainment process. Based on visual observations, Hussain (1983b) proposed that 'vortex stretching is the physical mechanism for entrainment and production in all turbulent flows'.

The subject of entrainment has, over the years, been studied on numerous occasions. It is interesting to note that many of the most revealing experiments into the entrainment mechanism have been visual studies, due of course to the global overview that such methods provide. It has been shown that the role played by large-scale structures in the entrainment process is most important and it is tentatively suggested that a quantitative visualization technique may aid the study of these structures, which may consequently improve comprehension of the entrainment mechanism.
2.3.5 Experimental Considerations

Having established the theoretical and conceptual aspects of the flow around a flat plate, the following review section will examine the experimental work undertaken on this particular bluff body model. The studies surveyed are primarily those that investigate the turbulent wake flow associated with the model, as it is this flow region that would be most conveniently studied by a quantitative flow visualization technique.

One of the first detailed quantitative investigations of the vortex wake associated with a two-dimensional flat plate model was conducted by Fage and Johansen (1927a). The experiments were made on a flat, sharp-edged rectangular steel plate. The plate was 7 feet (2.13m) long with a breadth of 5.95 inches (151.13mm), and was mounted vertically with small clearances between its ends and the floor and roof of a 7-foot wind tunnel at the National Physical Laboratory. It is now accepted that the gaps between the model and the tunnel floor and roof complicated the end-effects of this model which throws doubt on the twodimensionality of the flow. The length to breadth ratio was 14.12 and the aerodynamic blockage ratio was 7.1 percent.

Fage and Johansen reported a number of vortex shedding characteristics, which included:

(i) the determination that there was a region outside the wake and at some distance behind the plate where the velocity fluctuations were very regular,

(ii) the shedding frequency was constant throughout the outer wake regions, and

(iii) the centreline fluctuations were double the frequency of the vortex shedding frequency.

Strouhal numbers (based on body width and freestream velocity) were determined with the model at various angles to the flow direction, ranging from 12 to 90 degrees. The Strouhal number with the plate normal to the flow was found
to be 0.146 (uncorrected for blockage), determined over a Reynolds number range of $3.1 \times 10^4$ to $1.9 \times 10^5$. The Strouhal number was found to remain reasonably constant (0.146 to 0.149) when the plate was placed at incidences between 30 and 90 degrees to the freestream. Tyler (1931) and Hoole (1968) both confirmed this result although Hoole noted that at angles of incidence of less than 30 degrees, the shedding frequency was very weak and varied by up to twenty five percent between tests. Since the experiments of Fage and Johansen, other studies have been conducted on the flow around two-dimensional flat plates. Table 1 details the characteristics of these investigations.

FUNDAMENTAL EXPERIMENTAL FLAT PLATE RESEARCH

<table>
<thead>
<tr>
<th>AUTHORS</th>
<th>St</th>
<th>AR</th>
<th>t/h</th>
<th>Block. %</th>
<th>Cpb</th>
<th>CD</th>
<th>Comments</th>
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<tbody>
<tr>
<td>Bearman &amp; Trueman (1972)</td>
<td>0.140</td>
<td>28</td>
<td>0.20</td>
<td>7.0</td>
<td>-1.28</td>
<td>2.1</td>
<td>Rectangular Cylinders Critical t/h=0.6</td>
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<td>Davies (1975)</td>
<td>0.142</td>
<td>16</td>
<td>0.25</td>
<td>5.5</td>
<td>-1.24*</td>
<td>-</td>
<td>With End Plates</td>
</tr>
<tr>
<td>Donoso (1980)</td>
<td>0.146*</td>
<td>20</td>
<td>0.12</td>
<td>2.5</td>
<td>-1.27*</td>
<td>-</td>
<td>With End Plates</td>
</tr>
<tr>
<td>Fage &amp; Johansen (1927a)</td>
<td>0.146</td>
<td>14</td>
<td>0.03</td>
<td>7.1</td>
<td>-1.38</td>
<td>2.13</td>
<td>Definitive Study but Gaps Between Model/Wall</td>
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<tr>
<td>Fail et al. (1959)</td>
<td>0.109</td>
<td>20</td>
<td>0.16</td>
<td>1.5</td>
<td>-0.68*</td>
<td>1.50</td>
<td>3-D Model</td>
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<tr>
<td>Hoole (1968)</td>
<td>0.145</td>
<td>24</td>
<td>0.06</td>
<td>3.1</td>
<td>-1.50</td>
<td>2.02</td>
<td>Circular End Plates</td>
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<tr>
<td>Tyler (1931)</td>
<td>0.146</td>
<td>40</td>
<td>0.12</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Inclined Aerofoils (Water Channel)</td>
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</tbody>
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ADDITIONAL INVESTIGATIONS INVOLVING FLAT PLATES

<table>
<thead>
<tr>
<th>AUTHORS</th>
<th>Study Details</th>
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<tr>
<td>Abernathy (1962)</td>
<td>Theoretical &amp; Experimental Study, Free-Streamline Theory, Inclined Plates of Various Geometries, St=0.144, AR=14, Blockage=7.0%, St =0.15.</td>
</tr>
<tr>
<td>Bradbury &amp; Moss (1975)</td>
<td>Near-Wake Characteristics, Pulsed-Wire Anemometer, Uniform and Sheared Flows, St=0.14, AR=14, t/h=0.18, End Plates.</td>
</tr>
<tr>
<td>Geropp &amp; Leder (1983)</td>
<td>Time-Averaged LDA-Measurements in 2-D Bluff Body Wakes, Cpb=-1.1, Cpmin=-1.8 @ X/D=1.2.</td>
</tr>
<tr>
<td>Sullerey et al. (1975)</td>
<td>Near-Wake Similarity of 2-D &amp; Axisymmetric Bluff Body Models, St=0.154, AR=27, Blockage=5.0%, Pressure Measurements in Near-Wake.</td>
</tr>
</tbody>
</table>

* Denotes Corrected for Blockage

Table 1. Summary of Flat Plate Investigations
Fage and Johansen (1927a) measured the longitudinal spacing ratio of the von Karman wake vortices for a normal plate and with the plate inclined at angles to the freestream. The longitudinal vortex spacing ratio for the normal plate was found to be 5.25 D, which when combined with the measured vortex shedding frequency gave a longitudinal vortex velocity of 0.766 \( U_0 \), where \( U_0 \) is the freestream velocity. The equivalent values determined by Hoole (1968) were 5.30 D for the vortex spacing ratio and a longitudinal vortex velocity of 0.77 \( U_0 \).

Bearman and Trueman (1972) studied rectangular, sharp-edged, two-dimensional cylinders, from which the thinnest model (thickness to breadth ratio of 0.2) may be approximated to a flat plate model. The model had an aspect ratio of 28 and produced a longitudinal vortex spacing ratio of 5.9 D, corresponding to a vortex velocity of 0.76 \( U_0 \). Both Fage and Johansen (1927a) and Hoole (1968) produced mean velocity and pressure profiles of the wake.

The near-wake region of a flat plate is, however, highly turbulent and within the vortex formation region there are flow reversals, causing hot-wire anemometer results to be in error. Bradbury (1976) compared measurements obtained using both hot-wire anemometry and the then recently developed pulsed-wire anemometer. Comparative results were obtained within the first 4.0 plate widths of the wake, illustrating a significant degree of error associated with hot-wire anemometry data. In an attempt to overcome the directional insensitivity of the hot-wire, Cook (1975/76) developed a shielded hot-wire, but this device has not found universal acceptance. Perry and Steiner (1987) have developed a flying hot-wire, which through the superposition of a known velocity, determines flow reversals and allows the study of near-wake regions. Data collection using this device is, however, both time-consuming and complicated leading to its very restricted use. Hot-wire data obtained in highly turbulent, reversing flow regions should, therefore, only be regarded as qualitative flow information.
Limited time-averaged pressure and laser doppler anemometry measurements behind two-dimensional bluff bodies (including limited flat plate data) were reported by Geropp and Leder (1983), but such a sophisticated analysis system has seldom been applied to such basic flow configurations.

Fage and Johansen (1927b) examined vortex sheet structure and noted that shedding frequency was related not to the model dimension, but to the width of the wake. The previous review of wake similarity has demonstrated the foresight of their observation with regard to the importance of wake width. The combined experiments of Fage and Johansen were outstanding for their time and remain not only a source of inspiration and guidance to contemporary researchers, but also provide a valuable data base to the current flat plate design code produced by the E.S.D.U. (Code 70015 (1970)).

The publications reviewed above provide a comprehensive source of flow data so that the results of a quantitative flow visualization technique may be compared directly with similar results of past researchers. Since the initial, yet detailed studies of Fage and Johansen (1927a), relatively few experimental studies have been concerned with flat plate models (in comparison, for instance, to circular cylinders). This is not surprising as the model itself is uncomplicated in design and the flow past it may be assumed Reynolds number independent. Although having limited direct applicability to engineering structures, the model wake is highly turbulent, incorporating a vortex formation region with flow reversal and a classical von Karman vortex wake structure. This lack of complications reinforces its choice as a simple, yet 'interesting', test model upon which the capabilities of a new technique may be explored.

The preceding review sections have examined the general flow characteristics of flat plate and bluff body wakes. When comparing results for models of similar geometry it is important to identify fundamental flow attributes that may affect the values measured in wind tunnel experiments.
Identifiable experimental characteristics to be considered for two-dimensional models are principally:

(i) turbulence intensity of the freestream, and

(ii) two-dimensionality of the model flow, as influenced by the model aspect ratio or model/wall interaction effects.

The influence of turbulence intensity on flat plate mean drag was examined by Schubauer and Dryden (1935) and was more recently investigated by Bearman (1971). The effect of turbulence intensity on base pressure and flat plate Strouhal number were presented by Donoso (1980). The results indicate that variations of turbulence intensities which may generally be described as uniform flows (<0.5 percent) have no significant effect on the flow characteristics of the model. At higher turbulence intensities, Donoso noted a gradual decrease in Strouhal number and base pressure. The previously cited two-dimensional flat plate investigations were conducted in uniform flows possessing low turbulence intensities (<0.3 percent). It may, therefore, be assumed that variations in these low intensity values do not affect the comparability of the results quoted.

The two-dimensionality of a particular flow may be affected by the relative flow disturbance caused by model/wall interactions. A common experimental arrangement used to reduce such influences is the employment of end-plates which isolate the model flow from the disturbing flow conditions at the model's intersection with the wall. The degree to which a given model/wall disturbance affects the model flow is primarily determined by the model's length to breadth ratio. Donoso et al (1983) reported the use of adjustable slider/end-plate combinations to study the effect of aspect ratio on a two-dimensional flat plate model. Initial comparison of the base pressure distribution with and without end-plates at a fixed aspect ratio of 20 demonstrated clearly a base pressure dependence on both the use and dimensions of the end-plates.
Hoole (1968) demonstrated that the Strouhal number of his flat plate model was practically unchanged for aspect ratios greater than 15.0 (approximately). Toy and Fox (1986) noted the effect of aspect ratio of end-plate separation on square bar base pressures. The sketch below illustrates the base pressure regions they reported across the span of their bar.

![Graph showing base pressure regions](image)

Toy and Fox (1986) found a minimum aspect ratio below which the interference effects from the end plates merge to destroy the two-dimensionality of the model flow in the near wake. Whilst at larger aspect ratios the interference was less noticeable on the base pressure distribution. It may be concluded that the use of end-plates is obviously preferable and will, under normal conditions, improve the two-dimensionality of the model flow. Results obtained with end-plates would appear to be similar to results obtained at larger aspect ratios without end-plates. It would, therefore, appear that the variability of base pressures, drag coefficients, correlation coefficients etc., in two-dimensional flat plate experiments is principally due to the effects of aspect ratio in relation to the model flow two-dimensionality. Where possible, individual model measurements should be obtained in order to quantify the influence of these effects.

From the earlier visualization review (section 2.2.2), it would appear that a suitable means of visualizing a bluff body wake would be through the injection of smoke directly into the near-base region via a small-bore tube. The physical presence of the smoke-tube and subsequent smoke injection may conceivably influence the wake
characteristics. The possibility of such influences occurring is reviewed by the examination of wake afterbody studies (splitter plates) and a survey of known base-bleed effects.

The fact that artificially injected base-bleed reduced the drag of an aerofoil by delaying the onset of instability in its separated shear layers was demonstrated by Wood (1964) who investigated this phenomenon with a view to providing a means of vortex suppression. His results showed that the Strouhal number increased with base-bleed up to a maximum value approximately 20 percent higher than that recorded with zero bleed. These base-bleed tests were not initially extended, as it was believed that a simple geometric solution to the realisation of vortex suppression would prove ultimately less complicated. A later study by Igarashi (1978) overcame the need for externally 'pumping' base-bleed by providing a circular cylinder model with a slit cut along its entire span. This arrangement provided self-injection of fluid into the near-wake due to the high pressure around the stagnation region and the low base pressure. The effect of base-bleed on the oscillatory behaviour of an isolated cylinder model and on the buffeting phenomena of a cylinder model placed directly downstream of another identical model was investigated by Wong (1985). The test results indicated that a small quantity of bleed flow rate was sufficient to suppress flow-induced oscillations, and that there were upper and lower limits of base-bleed above and below which the application of bleed ceased to be effective. Wong, however, also noted that as the location for base-bleed was moved away from the normally adopted central position towards the sides of the cylinder, oscillation of the cylinder increased. It would appear that the volumetric base-bleed rates reported in these references would be far higher than the bleed rates proposed for a quantitative flow visualization technique, although no certain conclusions could be drawn without comparative studies of wake flow characteristics acquired with and without the requisite base-bleed. As the susceptibility of models of different
geometry to wake interference sources would appear to differ, such comparisons would obviously be required for all models studied.

Bluff body drag reduction (and in some cases suppressed vortex formation) through the use of splitter plates was demonstrated by Bearman (1965). It was reported that splitter plates forced the vortex formation region downstream. The results appeared to indicate that the distance of vortex formation was increased by the length of the splitter plate to a limit of 3.0 plate lengths where the flow reattached to the plate. Increasing the splitter plate length increased the Strouhal number to a maximum value before being reduced until complete suppression of vortex shedding occurred. It would appear that a diminutive after-body such as a small-bore tube should have no significant effect on the wake structure of a bluff body, but comparative tests, with and without the after-body should be undertaken in order to confirm this.

2.3.6 Intermittency Detection

The final section of this review surveys the existing methods of turbulence detection with particular attention to its application in turbulent flow intermittency.

It has been appreciated for many years that free turbulent flows such as jets, wakes and boundary layers exhibit a sharp interface between an interior region of turbulent flow and an exterior flow of non-turbulent or irrotational flow. Observations of a hot-wire signal placed near the outer edge of such a flow were first reported by Corrsin (1943) who identified two distinct signal contributions, indicating slow and smoothly varying velocity fluctuations indispersed with sections of much more rapid velocity fluctuations. The fraction of the total time that the signal is 'turbulent' is called the intermittency factor. More extensive studies of intermittency were conducted initially by Townsend (1948) and Corrsin and Kistler (1955).
Since the developments made by Corrsin and Kistler there have been many different versions of their intermittency detector. A simplified analogue circuit to detect intermittency factor was, for instance, presented by Bradbury (1964). Fiedler and Head (1966) used an improved version of Corrsin and Kistler's circuit, but developed a photo-electric smoke detector probe (previously described in section 2.2) in order to reinforce the validity of the intermittency results. Velocity signals from hot-wire anemometers are complicated by potential flow motions induced by turbulent fluctuations. Hedley and Keffer (1974) discussed in some detail the complications of turbulent/non-turbulent decisions in an intermittent flow. However, recent advances in digital computing have enabled alternative, quantitative evaluations of intermittency factor. Boisson et al (1983) numerically processed the second order derivative of a velocity signal using a finite differencing scheme as a turbulence detection discriminator.

In addition to velocity sensor turbulence detectors, passive contaminants have also been used to detect turbulence. Fiedler and Head (1966) concluded that smoke could be successfully identified as a turbulence indicator. Bilger et al (1976) used heat as a tracer and Wilson et al (1985) used propane gas and a flame ionization detector to study intermittency in a plume. Using tracer techniques should allow a less complicated detection system than the use of velocity probes as, ideally, there should be no trace of the contaminant outside the seeded flow. Temperature variations in a freestream flow demonstrate, however, that tracer detection may still be complicated, especially at the extreme edges of a turbulent flow where contaminant concentrations may be extremely low. Further discussions on this subject are to be found in section 5.3.1 which examines the experimental characteristics associated with intermittency detection and evaluation.
2.4 Summary

The reviewed literature in section 2.2 of this chapter has demonstrated that optical flow visualization techniques have, for some time, provided means of obtaining quantitative data from non-intrusive visualized images. The reduction of flow data information from holographic interferometry, for instance, has been shown to be a complex process and automatic data processing methods must be developed in order to fully appreciate the potential of the technique. Three-dimensional transient flows are extremely difficult to analyse using optical methods and require highly complex and specialised experimental facilities. The section also demonstrates that attempts have been made to use the less complicated procedure of smoke flow visualization to produce quantitative information. It has been shown that modern digital imaging techniques have been tentatively applied to visualized turbulent flows and that state-of-the-art technology is continually increasing the potential capabilities of a digital image analysis approach. The literature reviewed in section 2.3 examines the known principal flow characteristics of a two-dimensional flat plate model with regard to both theoretical and experimental aspects. The cited references demonstrate its applicability as a test model for the comparative evaluation of a quantitative flow visualization technique.

The following chapter introduces the concepts involved with digital image quantification in general and examines the constraints and requirements of real-time video digitisation and its application to on-line image analysis.
CHAPTER THREE

DIGITAL IMAGING AND REAL-TIME IMAGE ANALYSIS

3.1 Introduction

This chapter introduces the operational concepts involved in the acquisition of a digital image and demonstrates the timing constraints imposed on the acquisition and analysis of digital images in continuous or real-time applications. Digital image processing may be used to enhance, analyse, segment, compare or recognise images using a digital computer. The present study includes the enhancement of visualized images for presentation purposes but is principally concerned with real-time image analysis. Readers wishing to discover more about digital image processing techniques in general are recommended to the excellent publication by Pratt (1978). The individual sections of this chapter are as follows:

3.2 Image Sensors
3.3 Acquisition of a Digital Image
3.4 Imaging Facilities

Section 3.2 of the chapter examines various sources of images from which it is possible to obtain a digital image. The simplest and most established recording source is that of photography. Highly sensitive film emulsions provide an excellent means of recording low light intensity images such as those often produced in flow visualization experiments. Still-format cameras (most commonly 35mm SLR cameras) may be beneficially employed to study static images, whilst transient or high-speed events may require a cinematographic 'movie' camera or high-speed photography. Although, in general, less sensitive than photographic emulsions, video cameras may also be employed to examine static or transient images.
The standard vidicon tube video camera is now regarded as old technology and the latest video devices use solid state technology to improve performance and stability without sacrificing image resolution. Solid state video devices offer the possibility of variable framing rates, independent image integration period control and programmable scanning facilities.

Section 3.3 examines the quantification process necessary to produce a digital image. Spatial and grey-scale resolution criteria are considered for both slow-scanned and real-time imaging applications, and the signal-to-noise ratio of a video signal is examined with respect to its grey-scale quantification resolution. More specifically, the timing constraints and storage requirements of real-time digital imagery are also examined, with particular reference to the present turbulent flow study requirements. Display facilities and the cost considerations of a real-time digital imaging system are discussed in light of the above-mentioned characteristics.

Finally, section 3.4 describes a range of available digital imaging facilities with particular reference to those features outlined in the previous sections of this chapter, before providing a detailed description of the imaging equipment used in the present study.

It should be noted that this chapter introduces many of the technical terms involved in digital imaging which are used throughout the remainder of this dissertation. The following chapters assume knowledge of such terms and do not, therefore, re-define their meanings. The inclusion of this chapter within this dissertation reflects the Author's personal experience that although many scientists are widely aware of the results of digital image processing there remains a general lack of knowledge with regard to the physical processes involved in their production.
The discussions in this chapter are designed to highlight the limitations inherent to real-time image analysis, with specific reference to the present study. Consequently, there remain many interesting areas of digital image processing which are, unfortunately, beyond the scope of this chapter. However, further descriptions of digital imaging enhancement algorithms are outlined in section 7.1 of this dissertation, which introduces the further imaging applications undertaken by the Author.

3.2 Image Sensors

Having visualized a particular flow pattern by, for instance, such methods as those described in Chapter 2, the images thus produced may generally be observed by eye or recorded using either:

(i) photographic, or
(ii) videographic means.

With regard to photographic recording, images can be acquired as a single still image (with either single or multiple exposures) or as a sequence of images, commonly known as a 'movie'. Still image photography is a well-established, standard technique which when exploited to its limits, may itself be regarded as an 'art form'. Standard photography is of some use as a static flowfield recording medium but is far less useful in transient flow domains where no single image is representative of the temporal flowfield characteristics. The present study is concerned with the analysis of turbulent flows which are, in all cases, time-variant. Further references to photography will, therefore, be concerned with that of continuous or movie recording rather than still photography. Throughout the following discussions, all references to photography and videography will refer to monochromatic or 'black and white' recording media as, except in special circumstances, this type of information is extensively used in image analysis.
An example of real colour quantification may be found in section 7.7 of this dissertation which examines the visual analysis of shear stress sensitive liquid crystals.

Photographic film has for many years been the most popular medium for recording flow visualization images. In order to appreciate how films perform, with regard to lighting, grain-size, image definition etc., it may be beneficial to briefly examine the physical structure of the medium. Photographic film consists of five individual layers:

Layer -

(i) protects against scratches,
(ii) emulsion layer consisting of minute silver halide crystals,
(iii) adhesion substrate,
(iv) film base, and
(v) backing layer to prevent curling.

When exposed to light, the silver halide grains absorb optical energy and undergo a physical change. The development of an exposed film promotes a chemical change in the individually exposed grains which turn to silver (largely opaque at optical frequencies). The 'speed' of a film is determined by the amount of light needed to produce a given amount of silver at the development stage. (The 'ASA' speed scale is directly proportional to the sensitivity of the film). In general, the size of the film grains is also proportional to the film speed, with fine-grain films giving maximum image definition having low ASA speeds (below 64, say) and requiring a large amount of light.

The fineness of detail that a film can resolve depends not only on its graininess, but also on the light scattering properties of the emulsion and on the film contrast. As an example, a moderate resolution 35mm photographic negative may be comprised of approximately 2400 * 3600 individual picture elements or 'pixels', corresponding to a total of 9.0 million definite elements. A good resolution 35mm
negative may contain 18.0 million pixels, whilst a high resolution negative of larger format ('professional' cameras) may contain more than 500 million pixels. Standard cinematographical framing rates of 50 or 60 frames per second are normally achieved by stopping the progression of a film reel for the duration of each exposure. This stop/start filming arrangement restricts the maximum speed of the film through the camera and where high-speed objects or short-duration events are to be observed, framing rates of the order of thousands per second are often required. High-speed cinematographical cameras use a combination of rotating prisms and mirrors to expose short duration images onto a continuously moving film, which is fed through the camera at very high speeds. The mechanical principle of a high-speed photographic camera is, therefore, more complicated and operationally distinct from the working of a standard rate ciné camera. Examples of high speed photographic facilities include the Photec IV high speed camera manufactured by Photonic Systems Inc., U.S.A., which records images up to rates of 10,000 full frames (or 40,000 quarter frames) per second onto standard 120m reels of 16mm film. A similar rotating drum camera is produced by Cordin, U.S.A., their Model 350 recording 224 frames onto 16mm film with both variable exposure times and a variable filming rate of between 200 and 35,000 frames per second. Cordin's turbine-driven mirror options allow the Model 114 to record 25 frames at a rate of 5 million frames per second, whilst the Model 119 records 130 images at up to 25 million frames per second.

High-speed photography is a well established technique, which, as the above examples have shown, facilitates framing rates up to 10,000 per second with relative simplicity. To achieve high framing rates, very fast (i.e. high ASA) photographic emulsions must be used, necessitating high levels of illumination and producing relatively coarse-grain negatives.
At relatively low framing rates, the degree of blur for a fast moving subject may be reduced by the use of short duration flash exposures. Flash durations of a few microseconds are not uncommon for frame rates of a few hundred per second. The 'blur ratio' of the image can be simply defined as:

\[
\text{Blur Ratio} = \frac{(\text{subject velocity}) \times (\text{exposure duration}) \times (\sin \theta)}{\text{subject size}}
\]

where \( \theta \) is the angle between the camera lens axis and the direction of subject movement.

The use of lighting and electronic flash units in data acquisition from images has been reviewed by Miller (1981) and Pincu (1981).

The principal advantage of high-speed photography is the capability of capturing images of excellent spatial resolution at extremely high framing rates. The technique has been used extensively in the realm of fluid mechanics and has enabled complex high-speed events to be studied with unrivalled success. The technique is, however, severely limited by the developing and processing requirement of film once it has been exposed, and the need for an additional playback facility. Experimentally, it is difficult to be certain that the results of the acquisition will be adequate until the film has been processed and returned to the experimenter. Physically, the chemical development of a photographic film is a complex process which is normally beyond the control of those who are most interested in its quality. The variations in both the film structure and chemical processing stages may lead to uncertainties in the developed film's response to a given illumination level. Although this may not be critical to qualitative interpretation of a film, quantitative analysis using digital image processing techniques may be more susceptible to such variations.
The limitations outlined above have led to the adoption of videography, which through its more 'direct' operational nature allows immediate viewing of a recorded image sequence. At present, however, videography is not able to compete with high-speed photography in terms of spatial resolution or framing rates and its practical use is, therefore, more restricted.

The term videography describes both the acquisition and recording of images by electrical means. The following discussion is limited almost completely to the discussion of the acquisition of images via video cameras. The recording of video images is not an unimportant topic but is, fundamentally, beyond the scope of this chapter.

The two types of video camera currently available may be regarded as:

(a) Raster-scan cameras, and

(b) Solid state cameras.

(a) Raster-Scan Cameras

The design of standard raster-scan cameras has not undergone many alterations over the past 20 years. The best known and most established video system is the Vidicon-tube camera. Although later variations such as Newvicon, Chalnicon, and Plumbicon etc. have appeared, the operational principle of all these devices has remained the same and may be simply described in the following manner. The reflected light from a subject is focussed by an optical lens arrangement onto a photo-sensitive area. Electrical charge is lost from this area at a rate proportional to the illumination intensity of the image. Quantification of the lost charge is established by re-charging each individual photo-sensor to a pre-determined charge level via an electron beam which is controlled magnetically to produce a 'raster' sweep of the entire photo-sensitive area. In order to avoid spurious charging of photo-sensors the electron
beam must be switched off when moving across the image to start a new line or field scan. These 'off' periods are known as 'blanking' periods. In order to achieve a high display resolution, two sequential raster scans, or 'fields', may be combined to display a complete 'frame', these fields being displaced vertically to form an 'interlaced' picture. For a 'field' sensor camera (as used in this study) the sensor is scanned fifty times per second. For a 'frame' sensor camera, the 'odd' and 'even' fields are interlaced on the sensor and spatially displaced by one field line. The raster principle and interlacing concept of a video display are sketched below.

The standard United Kingdom 625-line video rate is 25 interlaced frames (equivalent to 50 fields) per second. Noel and Yates (1982) presented details whereby the scanning frequency of an electron beam was successfully increased to produce higher framing rates. The raster-scan camera they developed had a standard field integration time of 3.2 ms (equivalent to approximately 250 fields per second). Unfortunately, such cameras are not available as commercial items and must be specifically constructed. As in standard photography, when observing fast moving objects, blur is most often avoided by the use of short duration flash units or stroboscopes. In continuous light environments, blur may, however, be avoided by the incorporation of a rotating, short exposure shutter technique, a typical example of which was implemented by Silberberg and Keller (1981).
The image quality achieved by a raster-type camera is dependent on the following:

(i) mechanical accuracy of the scanning mechanism,
(ii) sensitivity of the photo-sensor,
(iii) stability of the electronic circuitry, and
(iv) optical quality of the imaging components.

Standard video tubes also suffer from 'burn-in', where a high intensity image may be recorded permanently by the tube sensor, 'lag', where a previous image is partially apparent in following images for a given lag time, and 'blooming', where a high light intensity image artificially increases the light intensities of neighbouring image elements. The most serious source of image inaccuracies is the mechanical raster scanning mechanism which causes unpredictable spatial representation and an increased signal noise contribution. Standard video tubes are, therefore, regarded as poor instruments for quantitative image analysis and have now been widely superceded by solid state devices.

(b) **Solid State Cameras**

Solid state video cameras are generally charge-coupled devices (CCD), although some are charge-injection devices (CID). The CCD sensor is by far the most common solid state device and its operation will therefore be described. Only the briefest of descriptions of CCD technology is given, for a detailed account the publication of Beynon and Lamb (1980) is highly recommended. The solid state image-sensing area is a matrix of photo-sensitive electrodes which are linked to form a photo-sensitive array. The 'photoelectric effect' charges the electrodes proportionally to the amount of light falling on the sensor. At the end of the illumination or 'integration period' the individual electrode charges are shifted electronically to a storage area in order to be read out as an electrical signal. The ability to shift images to this storage area after any desired integration period means that images can be read out and acquired at independent
rates, allowing cameras to have variable integration and output frequencies. Solid state cameras benefit from having no moving mechanical components, they are not affected by magnetic fields and can be constructed to be extremely compact. Burn-in, lag and blooming effects are not evident and excellent spatial accuracy is achieved through a combination of precision engineered square sensor pixels and an absence of a moving raster beam. The combination of all of these factors makes solid state sensors ideal for image analysis applications and for situations prone to vibration where raster-type cameras cannot be used.

Whilst early versions of CCD cameras possessed poor spatial resolution, more recent advances in construction techniques have realised medium resolution (512 * 512 element, or equivalent) devices which are directly comparable in resolution to standard raster-type cameras. The development of CCD arrays has been encouraged by their use in space satellites and although published details do not yet exist, far higher resolution arrays are rumoured to have been developed for such purposes. Other developments have led to 'snap-shot' CCD cameras, which acquire millisecond images to reduce blur, whilst maintaining standard (50 Hz) output.

High speed video recording facilities have developed from the INSTAR system produced by John Hadland (P.I.) Ltd., U.K., which recorded 120 full-frames or 240 half-frames per second via a lead-oxide monochrome tube sensor, to solid state sensor systems such as the Spin Physics SP2000 (Eastman Kodak Co.). The SP2000 uses a 192 * 240 pixel CCD sensor and records 45 seconds of film at 2000 frames per second (see Bixby (1981)). A split-screen/variable format capability allows a maximum partial-framing rate of upto 12,000 frames per second. The NAC HSV-200, records 200 fields per second in colour or monochrome onto a standard VHS cassette tape to give 60 minutes of recording and allows compatibility with many other standard video recording facilities.
The sensitivity of a CCD device is generally poorer than that of comparable raster-type video cameras, and whilst it is possible to obtain extremely sensitive video tubes, high sensitivity solid state devices are rarely available.

The spectral sensitivity of a video sensor is less uniform than that of a photographic emulsion. A typical monochromatic emulsion may respond in a fairly uniform manner to light wavelengths from 350 to 750 nanometers. The spectral response of a CCD camera is typically from 450 to 1100 nanometers, and is far less uniform across the entire range, the most sensitive and uniform region of sensitivity being over the range 600 to 950 nanometers (red to near infra-red wavelengths). In most fluid flow visualization experiments it has become standard practice to incorporate laser-light as the illumination source. In order to achieve the optimum sensor response, the wavelength of the illuminating source should be matched with the spectral response of the sensor.

All imaging systems suffer some degree of image degradation due to the optical characteristics of a typical camera lens arrangement. When using an optical system to compare light intensities within a particular image, there are certain definable errors that must be recognised. A primary source of error is lens aberration, causing a spatial non-uniformity of light distribution on the sensor. In addition to aberrations, the sensor sensitivity will generally be variable and may be very poor or even non-existent (i.e. dead pixels) in parts. The operating temperature also greatly affects the sensitivity of sensors and may induce drift in electrical circuitry. The most often employed solution to these problems is to calibrate the system before and after each experiment. Calibration can usually be accomplished by examining a neutral background (i.e. one of constant light intensity or grey-scale). Suitable corrections for the above error sources may be undertaken on static images through image processing techniques, if required.
As a note of caution, it may be wise to appreciate that video cameras of all descriptions are most commonly used for surveillance or general monitoring applications. They are, therefore, designed to operate over a wide range of illumination levels to suit environmental changes in lighting intensity. Furthermore, most applications use cameras remotely and require that they operate continuously without need for operator intervention. These demands have led to the development of auto-iris lenses and automatic light compensating circuitry. Either of these devices automatically adjusts the illumination level of an image to obtain an optimum intensity picture. Light compensation circuitry is not compatible with image analysis requirements and video devices best suited to image analysis are fully manual cameras or those that incorporate auto-iris lenses (as these may be easily replaced by a manual lens to avoid variable illumination errors).

The most obvious advantage of videography over photography is the immediate reproduction of the camera image and the instant replay capability of a recorded sequence. However, for present applications requiring framing rates greater than the industry standard of 50 fields per second, high-speed photography offers superior sensitivity and resolution. The future development of solid state devices should, however, improve the capabilities of medium resolution videography to allow higher framing rates without loss of image quality.

3.3 Acquisition of a Digital Image

The transformation of a picture into a digital image may take many forms. Acquisition systems range from inexpensive manual digitisation tablets to scanning microdensitometers, which may cost in excess of £250,000 (1988 prices). A digital image represents a continuous monochrome image by a number of discrete spatial coordinates where the brightness of each element is represented by a grey-level.
Consequently, the quantification of an image may be defined in both spatial and grey-scale terms, where the number of possible resolvable grey-levels depends upon the number of bits allocated to each picture element or 'pixel'. A binary image, for instance, uses only one bit per pixel yielding a purely black and white image. The dot-matrix picture shown below is a simple example of a two-bit image, there being three levels of grey (acquired via Computech Diplomat).

Higher resolution devices may digitise the grey-scale to twelve or more bit levels, giving a possible 1024 (twelve bits) grey values. The number of grey-scales quantified by a digitising system is normally related to the speed of image acquisition (slow-scan or real-time), which in turn determines the cost of the product. Image acquisition systems may be broadly classified as either:

(a) 'static', or
(b) 'real-time'.

A particular system's classification depends on the rate at which an image is digitised.
(a) Static Systems

A static system digitises a still-format image, such as a photographic print or negative. Speed of operation is often neglected to ensure high accuracy and definition. The simplest static image digitising equipment is a digitising tablet which may be operator-directed to various points of image interest where, upon request, locations are transmitted to a computer. Although simplistic in operation, such information may be sufficient, providing an extremely economic imaging solution. The highest precision static image digitisers are known as scanning micro-densitometers. Flat-bed or drum-scanner versions often use a single photomultiplier to automatically scan and digitise a matrix of image points. The resolution of these instruments may be as high as 100,000 * 100,000 pixels, requiring hours of continuous acquisition. More recently, linear CCD arrays have been incorporated into drum scanners to increase their operational speed. The acquisition of static images can be achieved with great accuracy, both spatially and in grey-scale resolution. The time and expense involved in obtaining such images limits the feasible number of images that can be acquired. To examine large numbers of images, it may be necessary to forego extreme accuracy and resolution, and adopt a real-time digitising system.

(b) Real-Time Systems

Real-time digitisation uses a video source and relies on 'flash' analogue to digital converters to continuously digitise an incoming video signal. In practice, therefore, 'real-time' may be defined as commercial video rates (either 25 frames or 50 non-interlaced fields per second). Higher rates are, of course, possible but prove to be expensive and for this reason it is customary to maintain compatibility with standard, commercially available equipment. This situation will inevitably change as solid state sensors offering variable framing rates become more widely used for industrial and research purposes.
Real-time systems are capable of digitising static or transient images, whereas slow-scan digitisers can only be usefully applied to static images. A CCD matrix format video sensor offers high spatial and temporal stability, medium image resolution and, perhaps, the afore-mentioned variable framing rates. Considering a matrix format of 512 * 512 and a refresh rate of 25 frames per second, it follows that a digitising rate of 8.0 MHz is required to continuously quantify the signal. The variable integration capability of a CCD sensor may, however, allow higher framing rates of partial-frame arrays. For instance, at a digitisation rate of 8.0 MHz a frame size of 512 * 64 pixels could be refreshed and digitised 200 times per second. Recent analogue converter advances indicate that 40.0 MHz rates may soon be widely available in commercial solid state imaging systems. Such a combination would allow a great deal of flexibility in the choice of framing rates and image resolution, the framing rate of the previous example, for example, being increased to nearly 1000 partial-frames per second. A frame rate of 1000 Hz has already been achieved by Bedworth (1983) using a 128 * 128 CCD matrix with a high-speed video recorder in a fluid mechanics flow visualization application. In certain circumstances, such a low resolution matrix may be adequate, in most applications however, a minimum resolution of 256 * 256 pixels is preferable. At this resolution, a 40.0 MHz digitisation rate would provide 600 frames per second, pre-supposing a sensor of sufficient sensitivity and an adequately illuminated image to yield a visible image over such short integration periods.

Having established the fundamental features of static and real-time digital imaging systems, it is necessary to examine the detailed operational requirements of an imaging system, with particular attention to the following features:

(a) Grey-Scale Resolution,
(b) Computer Memory, and
(c) Host Computer Access Time.
(a) **Grey-Scale Resolution**

The grey-scale resolution of a digital imaging system may generally range from 16 bits down to just one bit. The majority of real-time video digitisers offer 256 grey-levels (8 bits) or more, whilst a few are limited to 64 grey-levels (6 bits). The signal-to-noise ratio of an image sensor determines the number of grey levels or bits that may be reliably extracted from any particular digitisation system. Ideally, the digitisation process itself should possess a noise level equivalent to that of the original image signal, in this respect Jimenez (1984b) developed the expression;

\[ B = 0.17 \times (S/N) - 1.8, \]

where \( B \) is the number of bits, and \( S/N \) is the signal-to-noise ratio in dB.

As an example, a Vidicon system having a signal-to-noise ratio of 40 dB would, for instance, be designated a maximum of five bits per pixels, although to increase the confidence level of a single digitisation, only four bits would be recommended. Plate 1 show a similar scene digitised with 1-to 8-bit resolution, in order to show the degree of information contained in various bit levels. It may be observed that an increase in digitisation level improves both the grey-scale and spatial resolution of the image. Where spatial accuracy is a priority, 8-bit images are often employed, even though the individual digitised pixel values may contain a degree of image sensor noise. Image processing algorithms such as filtering and weighting may be applied to digitised images in order to reduce noise contributions and increase the signal-to-noise ratio (see sections 7.2 and 7.7 for further details and examples).

The digitisation accuracy of any sensor system may be improved by the process of 'averaging'. Averaging 100 images from a Vidicon camera, for instance, should improve the image quality from 4 bits per pixel to an averaged eight bits (the amplitude of the mean noise decreasing
proportionally to the square root of the number of images). Averaging can, however, only be applied to a static image and cannot be exploited (without image degradation in the form of blurring) in continuously moving, real-time situations. The signal-to-noise ratio of a CCD sensor is, however, considerably higher than that of a Vidicon camera and an image obtained by a standard CCD sensor can be usefully digitised to at least six or seven bits per pixel.

The present study is concerned with the real-time analysis of visualized flow structures. It may be deduced from the previous discussion that a solid state sensor offers the opportunity of digitising an image to six or seven bits (i.e. 64 or 128 grey levels). Until image sensor performance is improved, it would seem unnecessary, therefore, to use imaging systems offering more than 8-bit resolution for real-time analysis applications. Imaging systems offering 12- or even 16-bit resolution may be available but are, at present, limited to the examination of static images (using full grey-scale resolution). Having successfully digitised an image in real-time, the storage and/or analysis of the data contained therein must also be considered.

(b) **Computer Memory**

In order to capture a digital image of medium resolution, say 512 * 512 pixels, with a grey-scale level of 8 bits per pixel, 256 kilobytes of digital storage is required. Even with the rapidly developing capabilities of modern digital hardware, few computers can store such a vast image array in directly addressable memory, so an external image memory must be provided. Dedicated digital frame stores, sometimes known as 'frame buffers', must then be accessed by the host computer in order to examine the image pixels. Data transfer rates between host and frame buffer generally determine how many pixels may be examined within the timing limitations of a real-time digitising system (although dedicated single-board computers (SBC's) including image memory arrays may also be employed to implement image
analysis within board-level hardware). When examining a transient image in real-time it is necessary to consider the analysis of individual image fields. Standard rate real-time video digitising equipment will, therefore, examine 50 image fields per second, normally at a resolution of 512 * 256 pixels per field. The present study examines any number of images during an experiment, the maximum number normally being 20,000. To digitally store all of these images, over 2.5 gigabytes of storage would be required. Although optical storage facilities such as laser or optical disks can retain this amount of data, it is not, at present, feasible to consider their use in this particular application.

(c) **Host Computer Access Time**

The fundamental operational principle of the present study is to examine images in real-time without storing any of the original images. Writing sequential images to two independent halves of a frame buffer (known as 'butterflying') allows 20 mS of data analysis between the overwriting of each image. Accepting this time constraint, the amount of useful information that can be extracted from an image is obviously limited by the time required to access the image data and the time required to analyse and store the results into computer memory. The important parameters to be assessed when comparing digital imaging systems for real-time analysis applications are, therefore:

(i) 'pixel access time' from a host, and

(ii) host instruction frequency (normally quoted in 'mips' or mega-instructions per second).

As an example, the imaging system used for the present study has an average pixel access time of 0.8 microseconds. This data transfer rate indicates that a maximum of 25,000 pixels may theoretically be transferred to the host computer within the 20 mS available between incoming video fields. Assuming a 512 pixel horizontal resolution, this represents a total of 49 lines of an image. In practice, 4 instructions are required to perform the acquisition and storage of pixel
data which at an instruction rate of 1.0 million instructions per second dictates that only 4,000 pixels may realistically be transferred and stored within a 20 mS field time. In order to minimise the host computer instruction requirements and maximise the efficiency of the processing routines it is preferable to write all image analysis software in the most efficient manner. It is essential, therefore, that all pixel manipulating programming routines be written in a low-level assembler language rather than a high-level language (such as Fortran), and that the routines are streamlined to operate in the most expedient manner. To reduce host-computer transfers, many real-time digital imaging systems offer dedicated hardware options which can perform certain digital algorithms and functions within a 20mS field period. The most popular of such devices are known as Arithmetic Pipeline Processors which allow logical arithmetic operations of entire digital images in real-time, whilst other developments have been real-time histogram and feature extraction boards. The ultimate aim of such dedicated hardware options is to minimise host intervention and thus increase overall system efficiency.

The foregoing discussion has examined the acquisition of monochromatic digital images. The human eye can, however, distinguish less than thirty discrete grey-level shades at one observation, and it is thus preferable to use colour in display outputs to aid human comprehension. A widely used and often invaluable technique used in digital imaging is the facility of pseudo-colour display. Through this facility it is possible to display a grey-level as a colour via the assignment of separate red, green and blue (RGB) output values. Pseudo-coloured displays very often reveal less obvious grey-level patterns, allowing a human observer to gain a better understanding of an image. Plate 2 demonstrates how a complete grey-level display may be assigned particular pseudo-colours to aid human perception. The digitisation of a true colour video source is possible but until recently has been largely limited to use in the entertainment industry, and specialised industrial or
research applications. A true colour digitisation system for data analysis within the field of fluid mechanics may, however, be found in section 7.7 of this dissertation.

Display facilities often include hardware options such as variable zooming (2\(^*\), 4\(^*\), 8\(^*\), etc.), image panning and graphics capabilities. Hard-copies of displayed images may be simply obtained by direct still photography of the display monitor. (Aperture speeds of greater than a quarter of a second are preferable in order to avoid raster scanning interference, these long exposure times do, however, require the displayed image to be 'frozen' or static). Other hard-copy techniques include specialised, self-contained flat-screen instant cameras, ink jet plotters, electrostatic pen plotters and dot-matrix printers. More recent developments such as the GRAFTEL VP200 Video Processor, for instance, allow a colour video image to be stored and output to a hardcopy device such as a colour inkjet or colour matrix printer. The image format may be up to 1280 \(\times\) 1024 pixels and contain 8 to 64 different colours.

The cost of a real-time digital imaging acquisition and display facility will ultimately depend on all of the options and facilities previously discussed. Systems can range in capability and cost from binary digitisers costing £100 or so to sixteen bit, high resolution image processing suites costing in excess of £250,000 (1988 prices). In practice, many applications requiring relatively uncomplicated data analysis may be solved with a relatively simple digitising system. Where circumstances and requirements may change, a modular system allows maximum flexibility in system design and cost, allowing future expansion capability, if desired.
3.4 Imaging Facilities

The following section introduces a range of commercially available digital imaging equipment which encompasses a simple 1-bit binary digitiser through to dedicated image processing sub-systems. The examples quoted are, by no means, an extensive review of imaging equipment but are merely illustrations of various system options. The development of digital imaging facilities has progressed tremendously over the past six years (1982-1988) and it is envisaged that further developments will enable quite sophisticated imaging options to be available to many users at relatively low cost. The imaging systems detailed in this section are real-time systems which may be utilised for the study of transient video images.

The Diplomat video digitiser (Computech Ltd., U.K.) board is compatible with Apple II microcomputers and digitises an incoming video signal to a binary (1-bit) image having a spatial resolution of 280 * 192 pixels. The image is stored directly into computer RAM (graphics screen memory) and is, therefore, directly available to the host for analysis applications. The MicroScale IIIR (Digithurst Ltd., U.K.) is a 512 * 512 resolution image processing system which can be used with microcomputers such as IBM PC/AT, Sirius, Apricot, etc. The video data is stored in an external frame store (6-bit) and may be transferred to the host computer for enhancement, analysis and pseudo-colour display.

More sophisticated real-time image processing sub-systems are available for a range of main-frame or minicomputers. The Intellect 100/200 desk top image processing systems incorporate a 512 * 512 * 8-bit (256 grey levels) image memory with a video digitising rate of 10.0 MHz. The systems have a built-in DEC LSI-11/02 or /23 processor and possess a maximum pixel transfer rate of 100 kilobytes per second, representing a possible 2,000 pixels per image field. Additional system options include a digital video time-lapse recorder which allows the storage of upto 294 full
resolution images onto a Winchester disk at the fastest recording rate of 3.1 pictures per second. The Tigre 3000 system (France) has a maximum display format of 1344 * 1024 and features an expandable memory buffer of up to 24.0 gigabytes. Video signals are digitised at 30.0 MHz to 8-bit resolution and images may be transferred to optical or magnetic disks at a rate of 12.0 megabytes per second. The Tigre system is equal in resolution and display facilities to two American stand-alone systems which are possibly the most comprehensive real-time imaging systems presently available on the commercial market. The Trapix 5500 (Techexport Inc., U.S.A.) is a self-contained image processing system which may be combined with a dedicated DEC LSI-11 or VAX host computer. In addition to the standard imaging functions of equivalent systems, the Trapix 5500 has a dedicated pixel processor which employs a Texas Instruments 16/32-bit digital central processor capable of performing up to 5.0 mips, providing a full complement of arithmetic, logical and control instructions. Programmes that may use the pixel processor are, however, limited to 4.0 K words in length and the maximum pixel access time is quoted as 1.44 microseconds. The VICOM digital image processing system (VICOM Systems Inc., U.S.A.) is directly comparable to the Techexport system and both systems may be configured with various options to a possible system cost of approximately £250,000 or more.

The recently announced DEC/IPS Image Processing System (Kontron Electronics Ltd., U.K.) is a typical example of the most modern imaging sub-system concept. This unit has a display resolution of 1280 * 1024 and can be configured to possess 64 megabytes of image memory, enough for 10 seconds of sequential real-time image capture and display of 512 * 512 images. The video input is digitised at 20.0 MHz and recursive image processing functions (on-line subtraction, noise reduction, etc.) may be undertaken in real-time. The video memory board may be accessed at a rate of 20 megabytes per second, equivalent to 50 nS per pixel. The system also features a programmable image array processor and a pipeline
processor which both have instruction cycle times of 100 nS. The starting price of this system is approximately £20,000 but must be increased greatly to provide the various options mentioned above.

The stand-alone sub-systems outlined above are extremely expensive and due to their general purpose nature are not particularly efficient for real-time image analysis. Video digitising modules with optional accessory boards provide a flexible and economic solution to real-time imaging applications. In general, it is possible to perform all of the complex image processing functions available with the more expensive stand-alone systems, except that increased computation time may be required to calculate the appropriate algorithms.

The Datacube Inc. VG-124 board provides 640 * 512 * 6-bit video acquisition and display which combined with a 1.2 megapixel per second bus transfer rate is sufficient to analyse many real-time images. A more sophisticated real-time video digitiser module for the IBM Personal Computer is the PCVISION Frame Grabber (Imaging Technology Inc., U.S.A.) which offers 512 * 512 * 8-bit resolution with pseudo-colour display facility. A DEC Q-bus compatible imaging board system is also manufactured by Imaging Technology Inc., called the IP-512 system. The IP-512 modular imaging system was used in the present study and a detailed review of its general operational characteristics now follows.

The IP-512 system modules can be configured to perform image acquisition, graphics generation, and high-performance image processing functions, and the modules are plug-compatible with the Digital Equipment Corporation Q-Bus or the Intel Multibus. The system configuration used for the real-time analysis study consisted of a single AP-512 Analogue Processor and two FB-512 Frame Buffers. Additional options including an ALU-512 High Speed Arithmetic Image Processor, HF-512 Histogram/Feature Extraction Module and RGB true colour digitiser have been incorporated into additional
studies outlined in sections 7.7 and 7.8 of this dissertation. A schematic representation of the real-time imaging analysis system is shown below.

The analogue board (AP-512) conditions and digitises monochrome video input signals, and re-converts the digital data into analogue video output signals. Video signals may be taken from any standard, 'good quality' source, such as video cameras, video tape recorders, etc. The conditioned input signal is flash analogue to digital converted (ADC) at a rate of 10 million samples per second. The digital signal then passes through a 256-byte, software programmable input look-up table (LUT), and is sent via the Imaging Technology Video Bus to the frame buffers (FB-512). The processed video data is passed back from the FB-512 via the Video Bus, where it is transformed by LUTs and Digital to Analogue Converters (DACs) to be output on a display monitor. With three sets of LUTs and DACs, the AP-512 can produce pseudo-coloured signals. Four individual sets of input and output LUTs allow the efficient re-defining of a selection of input and output grey-scale values without having to re-programme the LUTs between each pseudo-colour selection.
The FB-512 frame buffers each contain 256 kilobytes of high speed random-access memory for storing a 512 * 512 pixel image frame. Individual pixels are 8-bits deep, providing 256 levels of grey-scale or colour information. The two frame buffers were interfaced to provide a total addressable frame buffer region of 1024 * 512 pixels. The FB-512 permits simultaneous host computer access through a dual ported memory, which is accomplished through an Input/Output (I/O) port, using X and Y Position Registers and a Pixel Data Register. Independent auto-increment and decrement of the X and Y registers is available which serves to reduce host intervention for image line acquisitions. The average pixel access time by the host computer Central Processing Unit (CPU) is 0.8 microseconds, yielding a pixel data transfer rate of 1.25 megabytes per second. Software selectable 2* zoom allows the acquisition of either, 512 * 512 interlaced frames, 512 * 256 or 256 * 256 non-interlaced fields. Pan and Scroll Registers allow the display of all parts of the image memory.

The host computer was a Digital Equipment Corporation (DEC) Micro PDP11/73 minicomputer. This multi-user machine is capable of supporting up to sixteen terminals simultaneously, but was restricted to a single-user system during imaging sessions to avoid external interrupts that would interfere with the real-time constraints of the imaging modules. The CPU is a sixteen bit processor and is thus relatively limited in directly addressable memory capability. In order to access its 1.0 megabyte of RAM memory, the processor invokes a memory management function whereby indirect or 'virtual' memory addressing is employed. The processor overheads involved in virtual memory access dictate that this type of memory access is generally too slow to be of use in all but the simplest real-time imaging applications. The Micro PDP11/73 also possessed a 31.0 megabyte Winchester system (hard disk) and two 400.0 kilobyte, 5.25 inch floppy disk drives.
The CCD video camera was manufactured in the United Kingdom by the English Electric Valve Company Limited. The camera is a variable exposure monochrome solid state device and has the model number P4320, Plate 3. The P4320 employs a P8602 frame transfer CCD sensor which enables the exposure period of each field to be manually adjusted over the range 1 mS to approximately 20 mS (control panel also shown in Plate 3) but operates at the standard fifty fields per second output rate and will therefore interface directly with conventional monitors and video recorders. In the standard 625-line mode of operation the P8602 provides 576 active lines in two interlaced fields, each line having 385 photo-sensitive elements. Optical geometry and positional accuracy are inherent features, provided by the precision array of 22 micron square pixels. The problems of 'burn-in', lag and blooming from which tube cameras tend to suffer are not present in the P4320. A +12 dB gain switch is provided for those applications where short exposure times are required and the illumination level is low. Use of the additional gain greatly reduces the signal-to-noise ratio of the device and was avoided (if possible) for image analysis purposes.
3.5 Summary

This chapter has introduced the most important of the details and definitions associated with real-time digital imaging. The chapter has examined the various means of quantifying both static and transient images and has outlined the restrictions imposed by a real-time video digitising facility if on-line image analysis is to be achieved from a standard video source. Finally, the digital imaging and video equipment used for the real-time analysis study is briefly described with specific reference being made to the foregoing discussion within this chapter.

The following chapter describes the experimental facilities and equipment used to examine the wake flow behind a two-dimensional flat plate model using both the digital imaging technique and traditional hot-wire anemometry.


CHAPTER FOUR

EXPERIMENTAL DETAILS

4.1 Introduction

The present study has investigated the use of a traditional smoke flow visualization technique combined with a modern real-time video digitising system to provide statistical data concerning turbulent flows. In particular, the wake flow behind a two-dimensional flat plate model has been studied, using both the digital imaging technique and hot-wire anemometry to provide directly comparable experimental results. The following sections of this chapter describe the apparatus employed in this study, the individual sections being as follows:

4.2 Wind Tunnel Facilities
4.3 Flat Plate Models
4.4 Pressure Measuring Equipment
4.5 Hot-Wire Anemometry
4.6 Flow Visualization Equipment
4.7 Details of Digital Image Acquisition
4.8 Digital Imaging Technique Assumptions

The details of the smoke tunnel and boundary layer tunnel are presented in section 4.2, with section 4.3 describing the flat plate models used in both tunnels.

Section 4.4 outlines the pressure measuring equipment, whilst section 4.5 describes the hot-wire anemometry equipment and software used in the present study. The calibration procedure of the system is described and the operation of a hot-wire probe in turbulent flows is discussed. The section also details temperature fluctuations encountered in the smoke tunnel facility and discusses the adopted temperature compensation method.
The equipment used for smoke visualization is examined in section 4.6. The smoke tunnel incorporates an efficient filtration system which allows constant introduction of smoke into the working section, whilst maintaining an open-return configuration in a laboratory environment. The filtration system does, however, create a finite back-pressure within the working section which dictates that the smoke contaminant for the visualization technique must be 'pumped' into the working section. Details of the illumination source and CCD camera traversing/alignment mechanisms are also given.

Section 4.7 details the programming mechanisms of the digital imaging system boards and demonstrates the operational steps involved in a general purpose real-time image analysis routine.

Finally, the more involved assumptions and errors associated with the digital imaging technique are outlined in section 4.8. The discussion begins with the examination of the adequacy of smoke particles to react to the motions of turbulent flows and is followed by a brief outline of smoke-scattered light. The section also examines optical sampling region size, camera lens considerations and image sensor sensitivity.

4.2 Wind Tunnel Facilities

All of the flow visualization experiments for the present study were undertaken in a specialised low-speed smoke tunnel facility situated in the Civil Engineering Department of the University of Surrey. Figure 1 is a schematic representation and Plate 4 is a photograph of this facility. In all future references, this tunnel will be known as the 'smoke tunnel'.
The smoke tunnel is an open-return, blow-down type which has working section dimensions 0.624m width * 0.75m height * 3.6m length, and since its construction in 1985 has been dedicated almost exclusively to flow visualization studies. Freestream velocities of up to 15 m/s are achieved by a Carter Howden Ltd '900A Airfoil Backward Bladed Centrifugal Fan' which produces a maximum volumetric flowrate of approximately 7.0 cubic metres per second (approximately 15,000 c.f.m.) and is powered by a 15 kW '160T Bull' motor. The working velocity of the tunnel is controlled by a KTK (Newtown) Ltd 6P15-CUB thyristor drive unit which allows continuous velocity control between approximately 1.0 and 15.0 m/s. The tunnel incorporates a wide angle diffuser with four 'filling' screens which leads to a settling chamber possessing a honeycomb flow straightener and two turbulence reducing screens. The air is uniformly accelerated into the working section by a three-dimensional contraction section having an area reduction ratio of 9:1. The tunnel exhibits an average longitudinal freestream turbulence intensity ($\sqrt{\bar{u}^2}/U_0$) of approximately 0.2 percent. A smoke filtration system, consisting of a diffuser and six 'Absolute' (Type E66WK/5) air filter units (manufactured by Vokes Ltd, Guildford) is located at the tunnel exit. The folded glass paper filters are 98.5 percent efficient for particle sizes between 0.01 and 4.0 microns (100 percent efficient for larger particle sizes). The sketch below illustrates general industrial and environmental particle sizes.

```
<table>
<thead>
<tr>
<th>Permanent Atmospheric</th>
<th>Temporary Pollution</th>
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<tbody>
<tr>
<td></td>
<td>Fog</td>
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<tr>
<td></td>
<td>Smokes &amp; Fumes</td>
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<td></td>
<td>Plant Spores &amp; Pollens</td>
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<td></td>
<td>Virus</td>
</tr>
<tr>
<td></td>
<td>Bacteria</td>
</tr>
<tr>
<td></td>
<td>Grit</td>
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</tbody>
</table>

0.01  0.1  1.0  10.0  100.0  1000.0

Particle Size (micron)
```
The filtration system allows the continuous introduction of unlimited volumes of smoke into the tunnel working section whilst maintaining an open-return configuration. There is a pressure loss across the filtration units which depending upon the volumetric flowrate of air through the tunnel may be as high as 35mm of water gauge. The slight excess static pressure thus created in the working section of the tunnel, necessitated particular attention being paid to the construction of all tunnel joints, and restricts the opening of the working section access windows during tunnel operation. Manufacturer's information with regard to pressure loss across the filtration system was initially used to predict the static pressures that would be encountered within the tunnel working section. Figure 2 illustrates the actual static pressure relationship with freestream velocity and indicates the comparative predicted pressure loss curve. The floor of the central working section unit is constructed of glass for visualization purposes, whilst the windows are constructed from clear cast acrylic sheet, frequently referred to as 'Perspex'.

Two independent wake traversing mechanisms were available in the smoke tunnel facility. The primary traverse consisted of a one-dimensional traversing unit which was used, without exception, for transverse wake measurements using hot-wire probes. Figure 3 shows a schematic representation of this traversing arrangement. The hot-wire probe and support tube were arranged to align along the mid-height plane of the working section and could be physically relocated to provide transverse traverses at specified downstream locations. The mechanism was driven by a stepper motor which was controlled by a Unislide Ltd manually programmable control unit. The second traversing unit (Figure 4) was a simply constructed rotational device which allowed limited three-dimensional probe location within the working section. Although the positional accuracy of an anemometry probe using this simple device was only of the order of \( \pm 2.0 \text{mm} \), this provided an inexpensive, quickly constructed yet invaluable three-dimensional traversing capability.
In addition to the smoke tunnel facility, a limited number of experiments were conducted in the boundary layer tunnel, also situated in the Civil Engineering Department. Figure 5 is a schematic representation and Plate 5 is a photograph of this larger tunnel facility. This tunnel is again of an open-return, low-speed, blow-down type having working section dimensions of 1.067m width * 1.372m height * 9.0m length, and a longitudinal turbulence intensity comparable with that of the smoke tunnel. The tunnel possesses a centrifugal fan which is driven by a 100 h.p. motor, controlled by a thyristor speed control. The area contraction ratio of this tunnel is less than that of the smoke tunnel at 5:1, although it does possess more turbulence reducing screens in the settling chamber. The tunnel boasts a fully computer-controlled, precision, motorised traversing mechanism with five independent degrees of freedom. A vertical 'sting' is attached to the traversing mechanism and protrudes into the working section through a sensor-activated, motorised sliding roof. The sting allows the relative positioning of measuring devices within the working section along axes parallel and perpendicular to the tunnel walls. In all future references, this tunnel will be known as the 'boundary layer tunnel'.

In both the smoke and boundary layer tunnels the freestream velocity was measured via pitot-static pressure tubes in their respective working sections, the velocity head being quantified by Perflow Instruments Ltd Micromanometers (measurement range 0-30mm of Water Gauge).

4.3 Flat Plate Models

Comparative hot-wire and digital imaging visualization results were undertaken in the wake region of a flat plate model. Whilst the majority of results were achieved in the smoke tunnel, a number of results were also obtained for a second flat plate model placed in the boundary layer tunnel.
The flat plates used were two-dimensional, thin, sharp-edged models constructed from HE30 aluminium. Experiments in the smoke tunnel were conducted on a 50.8mm breadth plate model which spanned the 0.75m height of the working section, presenting an area blockage ratio of 8.14 percent. Figure 6 shows the cross-sectional detail of the flat plate model including the location of the pressure tubing and tappings. The plate projected through the roof and floor of the working section and was restrained by clear cast acrylic locating assemblies which allowed the plate to be re-located vertically across the height of the working section and rotated about its axis. The length to breadth aspect ratio \((l/b)\) was 14.76, and the thickness to breadth ratio \((t/b)\) was 0.177. The 45 degree bevelled edges of the plate were machined sharp, all model surfaces being machined to a smooth, polished finish. The pressure tubing (1.47mm O.D., 1.0mm I.D. steel tubes) was cemented into recessed channels along the half-span length of the plate. The nine upstream tappings (and one centrally located base pressure tapping) were provided by 0.5mm holes drilled into the pressure tubing, and located at the mid-span cross-section of the model. The co-ordinate system and velocity component axes adopted for the model experiments are sketched below.

Experiments in the boundary layer tunnel were conducted on a 30.0mm breadth flat plate model. The model spanned the 1.067m width of the working section, presenting an area blockage ratio of 2.19 percent. The length to breadth aspect
ratio \(1/b\) was 35.6, and the thickness to breadth ratio \(t/b\) was 0.212. The plate was similar in machining details to those outlined for the smoke tunnel flat plate model and its cross-sectional view is shown in Figure 7.

Model end-plates were not used throughout the experiments in either tunnel due to the digital imaging technique visualization requirements. The smoke tunnel flat plate model had a relatively low length to breadth aspect ratio of 14.76. As demonstrated by Toy and Fox (1986) the two-dimensional model flow regime would undoubtedly have been improved through the use of end-plates to restrict model/tunnel wall interference (also see section 2.3). Unfortunately, the nature of the video analysis technique dictated that end-plates could not be incorporated, as such devices would have restricted the video camera field-of-view in the model near-wake region.

4.4 **Pressure Measuring Equipment**

The mean pressure distribution on the surface of the flat plate model was measured at the previously illustrated pressure tapping locations (section 4.3). Pressure tappings were read individually by connecting them (via short lengths of 1.0mm diameter tubing) to a Furness Controls Ltd Micromanometer (variable range), with a built-in pressure transducer (±0.5 V at full scale deflection).

The voltage output from the pressure transducer was offset, amplified and fed to an analogue to digital converter (ADC) board in the host Micro PDP11/73 minicomputer. Prior to data collection, the system was calibrated against the freestream pitot-static tube, the calibration software being similar to that discussed in more detail in the hot-wire section of this chapter (section 4.5), the voltage relationship, of course, being a linear function, \(E = A + BU\), rather than the King's Law relationship necessary for a hot-wire system (see section 4.5).
Although it is difficult to measure either mean or fluctuating static pressures to within any assured degree of accuracy in turbulent flows, the mean static pressure within the recirculating wake region was measured with a disc-static probe, as shown below. The probe consisted of a disc of 6.4mm diameter \( d \) with a hole drilled right through the centre of diameter 0.04 \( d \), this being mounted on the tip of a crank-ended tube.

A small spherical indentation had been made around each of the disc surface holes as this was claimed (Bryer and Pankhurst (1971)) to decrease the effect of turbulence on the probe reading. The probe was carefully and regularly cleaned in a solvent to remove any dust particles which were found to effect the readings. The disc-static probe readings were corrected by a suitable offset to obtain agreement with the surface base pressure reading. Whilst this was felt sufficient for the comparative nature of the pressure measurements required for this study, a more thorough investigation of the probe's pressure underestimation was previously reported by Baker (1977).
4.5 Hot-Wire Anemometry

4.5.1 Equipment

Constant Temperature Anemometry (CTA) equipment was used extensively for quantitative flow velocity analyses. The CTA equipment was manufactured by DISA and utilised single-sensor, straight-prong probes, type 55P11. The sensor wires were constructed of platinum-plated tungsten, having a diameter of 5 microns, and a length of 1.25mm, or 2.00mm. The probes were held by 4.0mm diameter supports which were themselves supported by mounting tubes for traversing purposes. A 56B10 Main Frame power supply unit housed two 56C10 general purpose plug-in bridges, the probes and bridges being connected via standard 50 Ohm 5.0m BNC cables. An overheat ratio of 0.8 was used extensively, defined as:

\[
\frac{\text{hot resistance} - \text{ambient resistance}}{\text{ambient resistance}} = 0.8
\]

The output from the anemometry system was neither linearised nor band-passed filtered. The possible errors introduced by the lack of such supplementary anemometry items with respect to turbulent flow applications is discussed in section 4.5.3. The anemometer signals were offset and amplified in order to provide an input voltage range of 0-10 Volts to an analogue to digital converter (ADC) board. The ADC board used was manufactured by Datel-Intersil Inc., U.S.A., and is plug-compatible with the Digital Electronics Corporation (DEC) Q-bus interface. The ADC board digitises a single-ended input signal to 12-bit resolution, giving a possible 4096 quantification levels. (Section 4.5.3 also discusses the quantification level of the anemometer signal with respect to the signal-to-noise ratio of the unfiltered anemometer output). The ADC has a maximum self-triggering 'burst sampling' rate of 50 kHz with a capability of multiplexing between 16 selectable input channels. The board was controlled and accessed directly by the host Micro PDP11/73 minicomputer.
In all instances, the hot-wire sensor-wires were located parallel to the model axes, i.e. the z-axis, and were restricted to the measurement of longitudinal velocity components.

4.5.2 Computing Software

The implementation of hot-wire anemometry in conjunction with the DEC Micro PDP11/73 minicomputer required the development of a complete suite of software routines. Until the realisation of this software, all previous hot-wire anemometry studies within the Civil Engineering Department had been conducted with 8-bit microcomputers. To increase the microcomputer precision, a 10-bit hardware analogue to digital converter had to be incorporated into their sampling systems which necessitated rather inefficient data transfer between the ADC and the microcomputer, restricting the system sampling frequency to approximately 2 kHz. In comparison to these and other microcomputer systems in use in the Fluid Mechanics Division of the Department of Civil Engineering, the 16-bit architecture of the PDP11/73 offers greater flexibility in both speed and precision with additional system features being a multi-user environment and batch processing facilities for off-line data analysis.

The hot-wire software utilities have been developed in both Fortran 77 and Macro 11 (machine-code assembly language). All general purpose programming functions such as terminal Input/Output and file management facilities were written in Fortran 77, whilst high-speed data acquisition and transfer routines between the host and ADC board were accomplished in Macro 11. The various hot-wire anemometry routines were written as modular units, capable of repeated use for various analysis applications. Situations requiring large amounts of high-speed data storage also accessed the efficient facilities of the IP-512 imaging system frame buffer memories (described in section 4.7). Under these circumstances, the two imaging frame buffers could not simultaneously be used for imaging purposes, but proved more
valuable as 0.5 Megabytes of directly addressable high-speed memory. In addition to the task addressable system memory (64K RAM) the Micro PDP11/73 itself possesses approximately 1.0 Megabyte of useful virtual memory space. Unfortunately, access to this virtual memory was found to be too slow for high-speed data acquisition applications (due to the software management routines required to accomplish the necessary memory mapping).

The Micro PDP11/73 hot-wire anemometry software package has been designed to use, as far as possible, similar 'menu' and programming presentation as the Commodore PET software which has been extensively employed within the Department of Civil Engineering.

In addition to maintaining compatibility with the existing software presentation format, the PDP11/73 hot-wire routines also offer the following features:

(i) Provision for simultaneous sampling of second hot-wire probe as freestream velocity and tunnel temperature indicator (see section 4.5.4).

(ii) Auto- and cross-correlation analyses with spectral analysis facility to determine the frequency domain components of a fluctuating signal (sections 5.3.2 and 5.3.3).

(iii) Calculation of third and fourth order moments of velocity signal distributions, i.e. skewness and flatness factor (as detailed below).

(iv) Intermittency factor and burst rate analyses using a high-speed digital sampling and detection procedure (see section 5.3.1).

(v) Optional simultaneous plotter output of traverse values, and large-scale post-acquisition plotting routines.

As mentioned in point (iii) of the enhanced software functions offered by the PDP11/73 hot-wire software suite, the following paragraphs will briefly outline the probability moments calculated for each mean velocity sample, these being typically compiled from samples of the order of 250,000 individual velocity samples.
Considering a velocity probability function, \( B(u) \), the following probability moments may be calculated:

The first moment, the mean value, is defined by,

\[
U_0 = \int_{-\infty}^{\infty} u \cdot B(u) \, du
\]

The second moment, the mean-square departure \( \sigma^2 \) from the mean value, \( U_0 \), the variance, is defined by,

\[
\sigma^2 = \bar{u}^2 = \int_{-\infty}^{\infty} u^2 \cdot B(u) \, du
\]

The third moment is defined by,

\[
\bar{u}^3 = \int_{-\infty}^{\infty} u^3 \cdot B(u) \, du
\]

which may be non-dimensionalised by \( \sigma^3 \), termed skewness \((S)\). A symmetric probability function has zero skewness, whilst a positive skewness indicates that large negative values of \( u^3 \) are not as frequent as large positive values of \( u^3 \).

The fourth moment, non-dimensionalised by \( \sigma^4 \) is termed the flatness factor \((F)\), defined by,

\[
F = \bar{u}^4 / \sigma^4 = 1 / \sigma^4 \int_{-\infty}^{\infty} u^4 \cdot B(u) \, du
\]

The flatness value is large if the values of \( B(u) \) in the tails of the probability density are relatively large.

The following sketches illustrate aspects of skewness and flatness factor (referred to more commonly as kurtosis, as detailed overleaf).

![Positive Skew](image1) ![Negative Skew](image2) ![Large Kurtosis](image3) ![Small Kurtosis](image4)

Higher Order Probability Statistics
A Gaussian distribution has a probability function defined by:

\[ B(c) = \frac{1}{(2\pi)\sigma} \exp\left(-\frac{(c-\mu)^2}{2\sigma^2}\right) \]

Through a change of variables this may be expressed as:

\[ E\{u^n\} = \frac{2^{n/2}\sigma^n}{\sqrt{\pi}} \int_{-\infty}^{\infty} x^n \exp(-x^2) \, dx \]

Due to the symmetry of \( \exp(-x^2) \), if \( n \) is odd, the moments all vanish, whilst if \( n \) is even, the second, fourth and sixth moments become, \( \sigma^2 \), \( 3\sigma^4 \), and \( 15\sigma^6 \)

The Gaussian flatness factor is, therefore, equal to 3, and because so many functions are compared against a Gaussian distribution, the term Kurtosis may be invoked which is merely, flatness factor minus 3. It is, however, quite common for flatness factor to be referred to as kurtosis (or kurtosis coefficient) although, strictly speaking, they are not equivalent.

In accordance with later hot-wire discussions involving the formation of 'zonal' (i.e. turbulent or non-turbulent) flow statistics, the continuous unconditional sampling of flow quantities (be they associated with turbulent flow or not) has been termed the 'combined' hot-wire measurements.

The present study facilities had no computer-controllable traversing mechanisms and thus, unlike the existing PET software, the PDP11/73 software does not, as yet, include automatic traversing routines. It is envisaged that future expansion of the PDP11/73 software would provide such a feature.
4.5.3 Calibration and Turbulent Flow Considerations

The mean longitudinal velocity and turbulence intensity experiments were conducted using two hot-wires, one to sense the freestream velocity, the other to sense the wake velocity (the necessity for this two-wire arrangement is explained in section 4.5.4). The calibration of these two wires, required twin channel amplifier and probe calibrations. The amplifier channels were calibrated against a precision voltage source allowing the CTA bridge unit to be calibrated against the analogue to digital converter (ADC). The CTA output was calibrated (with a sensor in an empty wind tunnel) against a range of freestream velocities, using the heat transfer relationship derived from King's (1914) Law. King's Law describes the heat transfer from a cylinder of infinite length and for use in hot-wire anemometry can be written as,

\[ E^2 = A + BU^n, \]

where, \( E \) is the anemometer output voltage, \( U \) is the fluid freestream velocity, and \( A, B \) are constants determined by a least-squares regression analysis to the calibration data.

King originally found the magnitude of the exponent \( n \) to be 0.5, but subsequent experiments by Perry and Morrison (1971) and Elsner and Gundlach (1973) have shown this exponent to vary from 0.45 to 0.5, depending upon velocity. Following DISA recommendations a King's Law exponent of 0.45 was used throughout the present study, and was found to produce calibrations with repeatably excellent correlation coefficients. A typical hot-wire anemometer calibration curve is shown in Figure 8.

The constants obtained from the amplifier and wire calibrations were used to form look-up-tables for the two hot-wire probes used. The tables were pre-calculated velocity values corresponding to each of the 4096 possible logic inputs from the ADC. Unlike the previously mentioned existing microcomputer hot-wire software, the size of these
arrays and the increased processing speed of the PDP11/73 dictated that look-up-tables for the squares of the velocity values did not need to be calculated. During subsequent probe measurements the digital value of a quantified analogue probe output was used to 'point' directly at its corresponding velocity value in the aforementioned look-up-table, alleviating the need for repeated and time-consuming velocity calculations (using the calibration constants). This type of 'software hot-wire calibration', whilst adequate for many applications, is limited by the need for these afore-mentioned velocity transformations. Considerable time-savings and experimental expedience would have been facilitated by the use of a hard-wired hot-wire linearizer, which would have allowed direct velocity calculations using analogue circuitry or digital integer multiplications. Cross-correlation measurements and the two-wire temperature compensation facility used in the present investigations would, of course, have necessitated a minimum of two such linearizers. Unfortunately, hot-wire linearizers were not available for the present study.

A technical note on the use of a hot-wire anemometer in turbulent flow was published by Hoole and Calvert (1966). They reported that in turbulent flow the probe supporting the sensor wire interferes with the local flow and that the degree of interference varies considerably with the orientation of the probe to the local flow direction. Such errors are quite distinct from, and in addition to, errors due to finite wire length, probe vortex shedding, vibration and sensor incidence to the local stream direction. Hoole and Grant presented a correction which defined an effective flow angle for two-dimensional flow. Unfortunately, the facility required to establish such a correction (multiple traverses of a crossed hot-wire anemometer) was not available in the smoke tunnel facility, forcing the analysis of uncorrected hot-wire data. Hoole (1968) stated that average errors for single hot-wire results in turbulent flows should be expected to be 2.0 percent for mean velocities and 5.0 percent for turbulence intensity.
components. In a bluff body near-wake, where strong flow reversal is evident, far greater errors should be expected and if possible, an alternative velocity sensor employed.

Signals from a hot-wire anemometer unit are complicated by spurious signals which have their origins in probe or wire interference, vibrations, mains 'hum' and electronic noise. A high percentage of spurious signal contributions may be removed from the turbulence signal through the use of low- and high-pass filters. Signal filtering is of particular importance in correlation measurements such as the determination of autocorrelation functions and/or spectral analyses. To prevent signal 'aliasing', it is important to filter an input signal to remove all components having frequencies greater than half the detection sampling frequency. Unfortunately, filtering of the signals was not possible, which led to an additional possible source of data error in the anemometry system. The PDP11/73 itself had an undesirable, yet not uncommon, computer characteristic of generating a great deal of electrical noise. Great care was required to isolate the sensitive anemometry units from this and all sources of air-borne electrical noise and ground-line interference. In order to examine computer-induced signal noise components and assess the signal ground quality, a digital inspection procedure was implemented in which a precision voltage source (from a battery supply unit) was input to the amplifier equipment. The signal was amplified and digitised at a high sampling rate (10 kHz) and output as a continuous voltage trace to a digital plotter. The following sketches illustrate typical digital plotter outputs, where (a) is a noisy signal, (b) is an improved signal, and (c) would have been an acceptable signal.
The constant input signal plots displayed distinctive short-duration signal spikes, which gave a visual indication of the relative occurrences of electrical noise. This method proved preferable to oscilloscope signal examination as the use of the oscilloscope itself may increase the noise content of the original signal, and plotter traces proved easier to compare than subjective judgements of oscilloscope traces.

In accordance with the noise considerations mentioned above, the previously quoted bit level to signal-to-noise relationship of Jimenez (1984b), \( B = 0.17 + (S/N) - 1.8 \), would indicate that to maintain a noise-free 12-bit digital signal, a signal-to-noise ratio of at least 80 dB would be required. Over the ADC input voltage range used, this would necessitate a noise level of less than 1.0 mV in 10.0 V, which from previous remarks would appear rather optimistic. This serves as a reminder that increased digitisation levels (i.e. 12-bits instead of 10 from an ADC) may not necessarily guarantee increased experimental accuracy.

4.5.4 Environmental Temperature Fluctuations

The smoke tunnel facility is located in an air-conditioned interior laboratory without windows or direct ventilation to the atmosphere. Operation of the hot-wire anemometer system
was found to be complicated by tunnel air temperature fluctuations (in excess of five degrees centigrade). These operating temperature fluctuations appeared to occur randomly and had a typical duration of anything between five minutes and one hour, being additional to the normal, gradual temperature rise associated with the long-term operation of the tunnel. The temperature fluctuations were found to originate from the laboratory's air-conditioning, which is connected as a network system to other laboratories within the same building. Preliminary wake velocity measurements using a single hot-wire with a single-valued, normalising freestream velocity were found to be subject to large errors (caused by these temperature fluctuations) and the results obtained were totally unsatisfactory.

Temperature compensation circuitry requiring specialised hot-wire probe arrangements is commercially obtainable but was not available for this study. Analytical temperature compensations could also be applied to the anemometer output with knowledge of the ambient air temperature and a suitable temperature compensation function. As no facilities were available for calibrating a hot-wire sensor at different freestream temperatures, this form of correction was rejected in favour of a less complicated two wire sensing arrangement. The adopted compensation system consisted of an upstream probe to sense the freestream velocity (this probe was physically and electronically matched as closely as possible to the wake sensing probe and was assumed to possess identical temperature-dependent characteristics) and a second probe located in the wake. The 'freestream' probe was sampled for each reading of the 'wake' probe, and an individual mean reference velocity incorporated into every wake velocity quantification. Compensations for temperature fluctuations were, therefore, realised by normalisation of the wake probe data by the indicated (temperature influenced) mean freestream velocity. Trial freestream comparisons proved that a compensation drift between the two probes of less than one percent occurred over a tunnel operating period of four hours with air temperature...
fluctuations of five degrees Centigrade. The following sketch illustrates the typical degree of hot-wire drift associated with the freestream sensing probe during a normal experimental run.

![Graph showing temperature fluctuations over time]

Nominal Freestream Velocity: 4.0 m/s  
Initial Ambient Temperature: 19.7°C  
Final Ambient Temperature: 23.0°C

The assumption necessary to justify this form of temperature correction is that the temperature remains constant over the sampling period required to acquire the wake velocity. This assumption would appear reasonable as the time required to acquire a typical velocity sample population of 250,000 was of the order to 50 seconds, much less than the shortest duration temperature fluctuation.

Corrections for temperature fluctuations were only necessary for direct wake velocity determinations. Correlation experiments using one or two wake probes required no such compensations, as the correlation product of a single or two similar wires will be identical regardless of gross temperature fluctuations. Having established the tunnel temperature variability, a simple thermocouple-type thermometer was used to monitor the smoke tunnel freestream temperature.
Whilst it had always been accepted that tunnels within the Department should be allowed to 'run up to temperature' before commencing experiments, this study highlighted two further features of tunnel operation.

(i) After starting the tunnel in early morning and maintaining a continuous constant freestream velocity for 8 hours, the tunnel freestream temperature was still climbing at a rate of almost 0.5 degrees Centigrade per hour.

(ii) In performing a typical hot-wire calibration, the operating temperature could vary by almost 2.0 degrees Centigrade between maximum and minimum velocities.

The obvious lesson to be learnt from these findings must be that regular hot-wire calibrations should be undertaken and, if possible, strict control of laboratory heating and ventilating systems should be maintained to reduce the ambient temperature drift within the tunnel environment.

4.6 Flow Visualization Equipment

4.6.1 Smoke Generation for Flow Visualization

The general requirements of a smoke suitable for flow visualization are primarily that it must be:

(i) dense,
(ii) of high visibility,
(iii) non-toxic, and
(iv) non-corrosive.

The smoke for the flow visualization experiments was produced by a commercially available generator unit manufactured by Concept Engineering Ltd, model name Genie Mark IV (Plate 6), which vapourised oil using a heated metal element. The volumetric production of smoke was controlled by a variable-pressure carbon dioxide supply which formed an
integral part of the generator operating system. This smoke generator is commonly used as an entertainment industry 'special effects' source, the generator oil being a Shell Ondina food quality white mineral oil, producing a dense, white smoke which is both non-toxic and non-corrosive.

Manufacturer's information concerning the smoke particle size distribution gave the average particle diameter to be approximately 0.5 to 0.6 microns, the overall distribution being from 0.1 to 5.0 microns, with 90 percent of the particles being less than 1.0 micron in diameter, illustrated below (approximate indicated distribution).

![Graph](image)

### 4.6.2 Introduction of Passive Smoke Contaminant

The principal requirement of this study was to visualize a wake flow and vortex street. Many forms of smoke visualization utilise upstream sources of smoke to produce streamlines around a body. Such visualizations allow an observer to indirectly infer wake structures from subsequent smokeline motions, which only remain visible within non-turbulent fluid. In contrast, the direct visualization of a wake flow may be achieved by smoke introduction directly into a model's separated base flow region. The principal assumptions made regarding the visualization technique are that the smoke injected into the model wake region is both effectively confined to the turbulent region and diffused throughout the entire wake by the action of wake turbulence (discussed further in section 4.8.1).
The smoke was introduced into the flat plate model wake via a small-bore (10.0mm external diameter) aluminium tube. The 'smoke-tube' spanned the entire height of the tunnel, was sealed at one end and perforated with 1.0mm diameter holes over 20.0mm of its central span. As described in section 4.2 the smoke tunnel operates with an excess working section static pressure which dictated that some form of balancing smoke 'pump' was required. To overcome this difference between model base pressure and the smoke source (at atmospheric pressure), a small variable speed centrifugal fan (Air Control Installations Ltd, Type VBM4) was utilised. Figure 9 shows a schematic representation of the complete smoke introduction system. The centrifugal fan operated on a variable 0-24V d.c. power supply and under normal isolated conditions had a maximum volumetric flowrate of 0.036 cubic metres per second (76 c.f.m.). Injecting the smoke into a wake region at a high volumetric flowrate would introduce an element of base-bleed and could artificially increase model base pressure, reduce the drag coefficient and effect the vortex formation process (see section 2.3). To avoid this undesirable base-bleed effect, the speed of the centrifugal fan was adjusted carefully until 'choking' of the smoke from the generator occurred. Continuous smoke introduction was subsequently achieved by increasing the fan speed slightly from this value to allow for natural base pressure fluctuations. The smoke tube was positioned as close to the rear face of the flat plate model as possible to avoid any 'afterbody' wake interference, which would be similar to the influence of a splitter plate (see section 2.3). To verify that the smoke introduction system had a negligible wake effect, a series of comparative hot-wire measurements was undertaken, the descriptions and results of which are to be found in sections 5.3.2 and 6.3.2, respectively. Whilst the results for the flat plate model indicated that the smoke-tube assembly had no significant effect on this particular model's wake, further comparative measurements should always be undertaken for different model configurations (especially for highly sensitive flows).
The illumination of the wake for image analysis purposes was achieved by the projection through the smoke-contaminated region of a 'raw' 5 mW Helium-Neon Spectra Physics laser beam. To provide accurate positioning, adjustment and mechanical stability of the illumination beam, the laser 'head' was mounted on and incorporated into a stepper motor controlled traversing mechanism. The traversing unit was mounted parallel to the tunnel working sections and the laser beam reflected at right angles via a specially coated silver-faced optical quality mirror. The mirror was mounted on a multi-rotational support assembly, which was itself mounted to the translation carriage of the traversing unit. The entire mechanism was totally enclosed whenever the laser was in operation due to safety considerations. Details of the laser traverse and mirror mounting assembly are shown in Figure 10.

Whilst all of the quantitative digital imaging analyses used the 5 mW Helium-Neon laser as a 'raw', single-beam illumination source, other qualitative investigations utilised a sheet illumination system similar to those more often employed for flow visualization experiments. The scanning mechanisms consisted of either a rotating mirror scanner or a somewhat cruder vibrating or 'resonant' mirror assembly, incorporating a simple, rotary solenoid.

The rotating mirror laser scanner consisted of a low-cost polygon motor assembly, model M-660-010-LVWOB, manufactured in the United States of America by the Lincoln Laser Company. The assembly featured a diamond-turned polygon mirror with 8 facets which, from manufacturer's information, possessed 88.0 percent reflectivity at 632.8 nanometers (Helium-Neon wavelength). The polygon was rotated by an integral AC hysteresis synchronous motor, having a speed range of 3,000 to 15,000 r.p.m. The synchronous motor was controlled by a variable speed control unit capable of driving fractional horsepower hysteresis motors over a total
range of 1,800 to 120,000 r.p.m (see Plate 7). The scanning mirror motor controller consisted of a variable frequency oscillator driven power switch with a two phase, 90 degree shifted output. The scanning controller unit (also shown in Plate 7) was assembled by the Author using a specialised motor driver card (model DC-2, Lincoln Laser Company, U.S.A.), including a plug-in speed indicator daughter board, displaying either 0.1 to 999.9 or 1 to 9999 r.p.m. (10 or 1 second setting, respectively). The controller unit circuit and connection details are shown in Figure 11. Drive power to the controller was provided by two 30 V, 5 Amp, variable power supplies, interconnected to provide ±30 V with a common current control.

A substantially greater amount of drive current was required to accelerate the motor to synchronism than was needed to maintain synchronism once achieved. Operation of the controller therefore required a large starting current and a subsequent current reduction once at synchronism (for continuous operation). If the power current was reduced too much, or if the synchronism controller frequency was altered whilst the motor was running, synchronism would be lost and increased drive current would again be required to restore proper operation. The operating motor also produced a substantial back EMF, and if the drive frequency was abruptly reduced, the motor-generated current surge could damage either the motor or drive controls. The motor leads were, therefore, protected by suitable line fuses.

Note: Power supply configuration for ± 30V @ 5.0 Amps
(current control common to both supplies).

Slave
1. Remove link between -sense and output terminals
2. Set CV/CI switch to Cl
3. Set voltage controls to zero

Master
1. Set for normal constant voltage operation
2. Voltage controls adjust overall voltage
The vibrating laser or 'resonant' scanner consisted of a rotary solenoid (12 V) with an optical quality mirror mounted to its shaft. This simple device was unidirectionally powered, with the solenoid's restraining spring providing the mirror's return stroke. Variable frequency power pulses were provided by one phase output of the previously described motor scanner controller. The vibrating 'solenoid' scanner possessed a relatively high inertia and was not specifically designed as an efficient vibrating scanner, the highest functional operating frequency being of the order of 60 Hz.

Apart from the obvious difference in the laser scanner and vibrating mirror frequencies, these devices also differed in scanning region sweep angle. Briefly, the angle of laser sweep produced by the rotary scanner was, of course, dependent on the number of mirror facets irrespective of scanning speed. The 8 mirror facets possessed by the previously outlined polygon scanner reflected a normally incident beam through an angle of 45 degrees, whilst a resonant mirror system would normally offer variable sweep angle as well as speed. From an illumination/analysis viewpoint, a rotational scanner offers a constant image illumination whilst a resonant scanner normally provides higher intensity illumination towards the edges of the scanner region (although specialist scanners may reduce this effect). The limited simplicity of the rotary solenoid dictated that the vibration frequency directly influenced the scanning angle, the highest scanning frequency providing a sweep angle of approximately 5 to 10 degrees. Unfortunately, the available laser source (5 mW Helium-Neon) was normally too low-powered to provide a reasonable image illumination using the rotary scanner for all but the most densely-seeded flows (section 7.4).

The illuminated wake was viewed through the glass floor of the working section by the E.E.V. Ltd solid state CCD video camera (previously described in section 3.4).
The CCD video camera was mounted vertically to a customised photographic tripod assembly, which having had the supporting legs removed, was mounted to the translation carriage of a second traversing unit. Details of the tripod assembly and traverse are given in Figure 12. The stepper motor controlled traversing mechanism provided translatory movement of the video camera, whilst ease of alignment and positioning were ensured by the four degrees of freedom incorporated into the tripod mount mechanism. The camera was continually cooled by a small air-blower fan unit and the entire assembly was 'blacked-out' during data acquisition to avoid stray light sources and reflections in the image.

The two traversing mechanisms were individually controllable through a manually programmable stepper motor controller unit (also manufactured by Unislide Time and Precision Ltd). Computer controlled stepper motor facilities were not necessary for this control requirement and would have provided little practical benefit to the general operational characteristics of the facility.

4.6.4 Image Blur Considerations

Having examined the various illumination arrangements incorporated in this study (section 4.6.3), it would seem relevant to briefly examine their respective image blur considerations.

The quantitative comparative study involving the flat plate wake was illuminated using the 'raw' 5 mW laser beam in a transverse or longitudinal orientation (depending on application). Whilst it is, perhaps, difficult to envisage image blur from a single line illumination, image integration will occur throughout the camera acquisition period. In effect, this may be equivalent to image intensity averaging over the camera integration period, which due to the solid-state 'snap-shot' facility may ideally be varied between 1.0 and 20.0 mS. The low relative transverse velocity of turbulent wake interfacial movements should
reduce image integration effects, whilst the CCD snap-shot facility would ensure further reduction in possible edge location blur. From a blur ratio viewpoint (previously defined in section 3.2), a typical experiment involving flow passing the camera at 4.0 m/s, with an image subject dimension of 500.0 mm, the following integration periods yield blur ratios and integrated flow region dimensions of:

<table>
<thead>
<tr>
<th>Integration Period</th>
<th>Blur Ratio</th>
<th>Integrated Flow Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.0 mS</td>
<td>16.0 percent</td>
<td>80.0 mm</td>
</tr>
<tr>
<td>16.0 mS</td>
<td>12.8 percent</td>
<td>64.0 mm</td>
</tr>
<tr>
<td>8.0 mS</td>
<td>6.4 percent</td>
<td>32.0 mm</td>
</tr>
<tr>
<td>4.0 mS</td>
<td>3.2 percent</td>
<td>16.0 mm</td>
</tr>
</tbody>
</table>

The rotary laser scanner provides 8 independent illumination scans per revolution, which when combined with the polygon rotational speed provides an indication of the minimum integration period required to illuminate a complete image scan. At the minimum snap-shot integration period of 1.0 mS, the minimum scanner speed should be no less than 125 r.p.m. At higher scanner speeds, the blur ratio may be calculated in a similar manner to that for a continuous illumination source.

The lower sweep frequency capability of the vibrating mirror enabled single laser sweeps to be matched with the image sensor integration period, reducing the image blur by illuminating any particular flow region for only a matter of microseconds. This type of laser sweep may cause differential image distortion due to relative image movement (depending on a combination of the degree of subject movement and scan period). The application involving the use of this illumination facility (section 7.5) was able to benefit from this type of illumination because of the low relative velocity of the image subject (boundary layer structure). To fully utilise this type of single-sweep approach the camera scan and illumination sweep periods should be synchronised to ensure complete image capture. This particular problem is discussed further in section 7.5.
4.7 Details of Digital Image Acquisition

The general physical characteristics of the video digitising equipment have previously been described in section 3.4. The following details will attempt to explain the programming mechanisms through which the real-time image analyses were realised. The majority of technical terms used throughout this section have been previously defined during the course of Chapter 3. Knowledge of these terms is, therefore, assumed and their explanations will not be re-iterated during this section.

General purpose programming on the host Micro PDP11/73 computer has been undertaken in Fortran 77. Programming in this language is not particularly efficient and tasks often occupy large amounts of valuable memory with unnecessary and cumbersome subroutines. Real-time image analysis requires:

(i) direct 'byte' or 'word' manipulation,
(ii) maximum processor efficiency, and
(iii) large amounts of high-speed directly addressable random access memory (RAM).

Image analysis programming was, therefore, executed directly in machine-code and written in an assembly language, which for the sixteen bit processor of the Micro PDP11/73 is called Macro 11.

Operation of the IP-512 imaging boards may be controlled directly by specific memory address location values. Each individual imaging board has a set of 8-bit registers which are mapped into the I/O page of the computer memory. These registers enable the host CPU to control and monitor all imaging functions, such as the acquisition of images and the accessing of pixel data from a particular frame buffer. The majority of the registers must be written to within either field or line blanking periods so as not to interfere with its real-time operations, whilst registers such as the pixel address and value registers may be accessed at any time.
The sketch below illustrates the imaging system control register arrangement.

Digital Imaging Control Registers

The analogue processor board (AP-512) has four 8-bit registers, which may be accessed either as individual byte locations or as 16-bit words. The AP-512 register map is shown below.

Register Base Address (17770020) + Octal Offset

0   LUT DATA
1   LUT ADDRESS
2   LUT SELECT
3   AP CONTROL

The three LUT registers (Base + 0, 1 and 2) allow the designation of all the various LUT values which are necessary to provide monochromatic or pseudo-coloured output images. The AP Control register (Base + 3) monitors and controls the video information such as the digital data format, input source and LUT group (display and acquisition R, G, B relationship with grey level).
The frame buffer board (FB-512) has sixteen 8-bit registers which may be grouped into the following eight 16-bit register map.

Register Base Address (17770000) + Octal Offset

<table>
<thead>
<tr>
<th>Octal Offset</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>X-POSITION</td>
</tr>
<tr>
<td>2</td>
<td>Y-POSITION</td>
</tr>
<tr>
<td>4</td>
<td>PAN</td>
</tr>
<tr>
<td>6</td>
<td>SCROLL</td>
</tr>
<tr>
<td>10</td>
<td>FB CONTROL</td>
</tr>
<tr>
<td>12</td>
<td>RESERVED</td>
</tr>
<tr>
<td>14</td>
<td>MASK</td>
</tr>
<tr>
<td>16</td>
<td>PIXEL DATA</td>
</tr>
</tbody>
</table>

The Pan and Scroll registers (Base + 4, 6) locate the memory region to be displayed and written to, whilst the Mask register (Base + 14) protects specified bit levels within the memory region. The FB Control register (Base + 10) determines the activity of the imaging system with regard to display format (continuous, frozen) and size (512 or 256 dimensions), enabling auto-increment of X and Y registers and the monitoring of odd/even fields and blanking periods.

The X- and Y-position registers (Base + 0, 2) specify the address of a pixel within the frame buffer memory to be accessed by the host CPU for a write or read operation, via the Pixel Data register (Base + 16). The auto-increment facility allows either or both of the X- and Y-position registers to be automatically incremented after each read and/or write operation which reduces the number of host instructions required to access complete (512 data elements) pixel lines.

The following discussions do not refer directly to the programming demands of these individual system registers but instead reference merely the function of the system as an
operational unit. As an example of the general programming capability of the IP-512 imaging system, a fundamental image acquisition and analysis sequence for an analysis application may be organised in the following manner.

The imaging boards are initialised and programmed to continuously digitise full-format, non-interlaced sequential images, providing fifty fields per second of continuous digital data. The image format in this mode is 512 pixels horizontally by 256 lines vertically. Each frame buffer, being 512 * 512 format, can accommodate two such images, whilst the field blanking periods may be detected by sensing a particular 'bit' in the FB-512 Control status register. The relative position of the digital image in the frame buffer is specified after each detection of the blanking period via the Pan and/or Scroll registers so that successive acquisitions are directed to opposite 'halves' of a frame buffer. In a particular sequence, the first frame is directed to the top half of the frame buffer, the second to the bottom, the third to the top and so on as illustrated in the following sketch. (This type of image storage is called 'butterflying' for obvious reasons).

![Image Storage Diagram](image.png)

Image analysis of one field may be continuously undertaken whilst the next image is being written to a separate part of the FB-512 memory. At the start of the following field's blanking period, the most recently stored image may be analysed whilst the older image is updated by an incoming
digitised field. In this manner, maximum time (i.e. 20 mS) is available for uninterrupted image analysis, without fear of corrupting an incoming image. Image analysis generally consists of retrieving a specified image area to a RAM memory buffer, allowing detailed statistics to be processed from the most efficient memory access region. Having designed a suitable analysis routine, timing constraints may be simply verified by the precise timing of a few thousand continuous analyses (should return less than 20 mS per analysis) or from trial images. For instance, the acquisition and analysis of 5,000 images should take precisely 100 seconds. If the analysis routine has an error in it or is simply too complicated, more than 100 seconds would be required. If available, timing details of analysis routines may also be obtained from a logic analyser. An analysis programme should always be tested in this manner for the 'worst possible case' to be completely confident in its continuous real-time operation. The 'worst case' was either digitally pre-programmed into the frame buffer memory and not updated, or provided through direct camera digitisation of a suitable image simulation.

4.8 Digital Imaging Technique Assumptions

The digital imaging technique proposes to study the dynamics of a turbulent wake flow through the observation of smoke particle concentrations, as indicated through variations in scattered light intensity from a constant energy illumination source. It is obvious, therefore, that the technique will not directly observe fluid motions but, instead, will observe the behaviour of a cloud or 'aerosol' of smoke particles which, it is assumed, is directly influenced by the fluid motions. Whilst the proposed studies are designed to quantify turbulent flow properties and not the diffusive nature of smoke particles released into a turbulent wake, it may be observed that the two physical processes are mutually dependent. This section, therefore, examines the known physical attributes of particle
behaviour, their light scattering properties and the assumptions made with respect to the imaging of the light intensities through to a typical image sensor. With regard to the particle behaviour and light scattering properties of aerosols, Readers are recommended to the publications of Fuchs (1964) and Friedlander (1977), on which much of the following discussion is based.

4.8.1 Smoke Particle Adequacy

An ideal smoke particle must have small inertia, it must not evaporate, sublime, coagulate, or react chemically with the experimental fluid. In addition to these properties, the identification of turbulent flow through the detection of smoke particles relies on particles injected into a wake flow remaining within the turbulent flow region. The important characteristic in this respect is that the particle diffusivity \( D \) of the suspending medium is much smaller than the kinematic viscosity of the smoke particles \( \nu_S \). This relationship is characterised by the Schmidt number \( N_{sc} \), which must be greater than unity. The following table illustrates the diffusivities and Schmidt numbers for spherical particles in air (at 20 degrees Centigrade and atmospheric pressure).

<table>
<thead>
<tr>
<th>Particle Diameter ( d ) (( \mu \text{m} ))</th>
<th>Diffusion Coefficient ( D ) (( \text{cm}^2/\text{sec} ))</th>
<th>Schmidt Number ( \nu/D )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001</td>
<td>( 5.14 \times 10^{-2} )</td>
<td>2.92 \times 10^0</td>
</tr>
<tr>
<td>0.01</td>
<td>( 5.24 \times 10^{-4} )</td>
<td>2.87 \times 10^2</td>
</tr>
<tr>
<td>0.05</td>
<td>( 2.35 \times 10^{-5} )</td>
<td>6.39 \times 10^3</td>
</tr>
<tr>
<td>0.10</td>
<td>( 6.75 \times 10^{-6} )</td>
<td>2.22 \times 10^4</td>
</tr>
<tr>
<td>0.50</td>
<td>( 6.32 \times 10^{-7} )</td>
<td>2.32 \times 10^5</td>
</tr>
<tr>
<td>1.00</td>
<td>( 2.77 \times 10^{-7} )</td>
<td>5.42 \times 10^5</td>
</tr>
</tbody>
</table>

Table 2. Particle Diffusivities and Schmidt Numbers

It is obvious that where diffusive flow properties are to be studied, flow seeding in this manner would not be suitable and indeed, since the diffusivities of the smoke particles
and air molecules differ so widely, the smoke particles are limited in their ability to follow the fluid fluctuations. Particle behaviour often depends on the ratio of particle size to a characteristic length. The mechanisms of heat, mass and momentum transfer between particle and fluid depend on the Knudsen number, \( 2l/d \), where \( l \) is the mean free path of the fluid. As a good approximation,

\[
l = \sqrt{\frac{\pi m}{2kT}}
\]

where, \( \nu \) is the kinematic viscosity of fluid, \( m \) is the molecular mass, \( K \) is Boltzmann's constant, and \( T \) is absolute temperature.

At normal temperature and pressure, the mean free path in air is about 0.065 microns. Where the particle diameter is much greater than the mean free path \( (l/d \ll 1) \), the fluid behaves as a continuum with the particle drag being much greater at the same relative velocity than for free molecular flow \( (l/d \gg 1) \). The velocity amplitude ratio for a spherical particle acted on by Stokes drag with the Cunningham correction is given by,

\[
u'/u = \frac{1}{\left[1 + (2\mu f/a)^2\right]^{1/2}}
\]

where, \( a \) is \( 18 \mu/\rho_D D_p^2 (1 + k l / D_p) \)

\( u' \) and \( u \) are the r.m.s. velocities of the particle and gas, respectively,

\( K \) is the Cunningham constant (1.8 for air)

\( l \) is the mean free path of the fluid

Accepting a 10 percent loss in velocity response \( (u'/u = 0.9) \) and assuming \( l = 10^{-5} \) cm, \( \mu = 1.9 \times 10^{-4} \) g/cm sec., the frequency limit for particles of less than 1.0 micron in diameter is greater than 22 kHz. Whilst no experimental data was available to confirm this assumption, it would seem reasonable to assume that the wake turbulence energy was concentrated in frequencies of less than 10 kHz, allowing the smoke to adequately follow the turbulent fluid fluctuations.
Although no figures were available, the rate of evaporation of the smoke particles is set by molecular diffusion and particulate surface area. A more thorough quantification of evaporation for an oil smoke by Rosensweig et al (1961), calculated the initial percentage rate of decrease of particle diameter due to evaporation to be approximately 5 percent per second. The average residence time of a smoke particle in the wake (locations < 12.0 X/D) for the flat plate was typically of the order of 0.2 seconds, which may be assumed to indicate that evaporation effects would be negligible.

Particle coagulation, through Brownian motion and the dominant turbulence structures in the flat plate near-wake would appear to be particularly difficult to predict, the basic process being non-linear. In practice, Brownian motion collisions may be studied under experimental conditions with the change in scattered light being observed with time, and although expressions may be developed for this type of collisions, the turbulence-induced coagulation problem would appear dominant. Friedlander (1977) discussed coagulation problems in detail, but it would not appear possible to predict the possible turbulence-induced coagulation effects.

4.8.2 Smoke-Scattered Light

When smoke particles interact with light, two different types of process may occur. Firstly, the energy received may be re-radiated at the same wavelength or secondly, re-radiation may take place in all directions with different intensities (dependent on direction), called scattering. Alternatively, the radiant energy may be transformed into other energy forms, such as heat, chemical reaction of radiation or a different wavelength, which is collectively referred to as absorption. In the visible range, light attenuation by absorption is dominant for black smokes, whereas scattering controls white smokes. The total energy removed from an incident beam on a particle, the extinction energy, is the sum of the scattered and absorbed energies.
Where the particle diameter is much less than the incident wavelength, the scattering is controlled by Rayleigh scattering, whereas for diameters much larger than the incident wavelength, the particle extinction laws govern. For light in the visible range, the wavelength, $\lambda_c$, is of the order of 0.5 microns, transition between the two regimes is governed by classical electromagnetic theory, but computations are complex. The following sketch illustrates light scattering efficiency for different particle sizes. The peak may be seen to occur in the range corresponding to the wavelengths of the scattered light in the visible range.

Light Scattering Efficiency (expressed as light scattered per unit mass of particles)

![Graph showing light scattering efficiency vs. particle diameter.](image)

The scattering of light by smoke particles (average diameter 0.5 to 0.6 microns) may be related by Mie's equations (see Van De Hulst (1957)). Under normal conditions it may be assumed that if $N$ like particles exist in a small control volume $V$, then the light scattered from that volume will be $N$ times that scattered by one particle. The spectral intensity of the irradiated light depends on:

- (i) particle diameter,
- (ii) index of refraction,
- (iii) intensity of the incident beam, and
- (iv) angle through which the scattered light is detected.
In general terms, the most efficient direction to observe scattered light is in 'forward-scatter' (looking directly back at the source), the next best is 'back-scatter' (looking in the same direction as the source), with the worst case being 'side-scatter' (at right angles to the source direction). Experimentally, the most common viewing angle for visualization studies is at 90 degrees to the illumination source (mainly due to geometric and physical considerations) which, of course, produces the worst possible light scattering arrangement. Where qualitative viewing angles may suffice, the best illumination results may be achieved by viewing at an angle which allows some degree of forward scattering.

Due to the relatively low power laser source (5 mW He-Ne) and the relatively low CCD array image sensor sensitivity, smoke concentrations for the visualization studies were unavoidably high, leading inevitably to some degree of optical attenuation. Optical background noise such as stray extraneous light was, however, eliminated by the careful masking of all incident and reflected light sources.

4.8.3 Optical Sampling Region Size

All turbulence measuring devices are affected in their resolving power by their finite size and the accompanying phenomenon of space averaging. In the case of a hot-wire anemometer, the significant dimension in this respect is the sensor length. The digital imaging technique may study varying flow volumes, depending on the illumination source and camera lens arrangement. Generally, the laser beam illuminated a cylinder of flow having a diameter of between 1.5 and 2.0mm (depending on the experimental configuration). The camera lenses available ranged from 4.8mm focal length (wide angle) to 25.0mm (telephoto lens), whilst most applications used an 8.5mm focal length lens. This lens provided a field of view of approximately the entire working section width (500.0mm at tunnel mid-section) and consequently determined that a digital pixel width
represented approximately 1.0 mm width of flow. Lenses of larger focal lengths provided greater accuracy still, indicating that the limiting spatial resolution dimension of the system was the laser beam diameter. It should be noted that the frequency response of a hot-wire sensor is often limited by its spatial resolution, rather than the wire's response.

Consider a flow case where the freestream velocity approaches 30.0 m/s, with the smallest turbulence scales being approximately 1.0 mm, the frequency response required would be of the order of 30 kHz (30.0/0.001). For a typical sensor length of 1.0 mm, the smallest scale disturbance that may be confidently recorded must be of the order of 5.0 mm in length scale, corresponding to a 6 kHz frequency response. Having established this example, it would appear that the sampling volume and its effect on frequency response due to space-averaging were not a problem compared to the far greater limit of the 50 Hz sampling frequency of the video system. Complex analysis of this problem is possible but would be trivial in comparison to the video rate frequency limitations. It would, however, appear that for any future proposed system incorporating image scanning frequencies of the order of 1.0 kHz, the illuminating region dimensions should be reduced as far as possible to obtain optimum system resolution. Provision for laser optics and 'close-up' lenses would possibly ensure sub-millimetre sampling region dimensions and ensure the requisite frequency responses.

4.8.4 Camera Lens Considerations

Light waves passing through a transparent medium are subject to both refraction and dispersion. As a result of dispersion, lenses may suffer from chromatic aberration, causing different colours to be focussed at different distances from the lens. The spherical curvature of a lens surface leads to spherical aberration and astigmatism. It is clear, therefore, that spatial distortion of an image and loss of light due to absorption and reflection must also be
considered when attempting precision imaging. The degrees to which any of the above phenomena affect the quality of a given image depends largely on:

(i) focal length of the lens,
(ii) arrangement of the lens components,
(iii) quality of the lens materials, and
(iv) lens aperture used.

In general, the larger the focal length and the smaller the aperture, the more insignificant these errors become, whilst the quality and mechanical accuracy of a particular make of lens is normally reflected in its relative cost. Unfortunately, unlike photographic cameras, video cameras are seldom used for high precision, low distortion imaging applications and few high quality lenses are commercially available. Within the experimental arrangement under study, large focal length lenses and small apertures were also seldom suitable, due to the global nature of the analysis and unavoidably low intensity smoke particle scattering.

In all instances, the only accurate method of spatial distortion or light loss compensation, is to accurately calibrate the video image of a metred and/or constant illumination object (such as a mensuration grating). Laser illumination should also ensure that the majority of the scattered light received by the sensor is of one wavelength, reducing any chromatic aberration effects.

4.8.5 Image Sensor Sensitivity

The sensitivity of raster-type video cameras and CCD solid-state devices has been previously discussed in section 3.2. The comparisons made reflected the overall sensitivity of the particular sensor types, indicating that raster-type cameras could be far more sensitive than a comparative solid-state device. The use of video cameras as image analysis sensors, however, demands that attention also be paid to individual picture element and localised image
sensor sensitivities. Local pixel regions of non-uniform response may create artificial light gradients or misleading features, which if not recognised could lead to false analytical interpretations. In addition to variable pixel response, certain pixels of a CCD array do not function at all. These so-called 'dead' pixels are physically linked by the manufacturer to a neighbouring pixel so as not to produce isolated black pixels in the video signal output. The number of dead pixels in a CCD array matrix determines the array grade and, of course, its relative cost.

With an increasing production of CCD array devices, manufacturing methods have improved, and dead pixels are becoming less common in production equipment. Nevertheless, if such pixels are present, these should be identified and avoided for image analysis applications if possible. It would also seem a common CCD feature that individual picture elements have only an average uniformity in their response to light intensity and once again, absolute knowledge of every pixel's response characteristics could only be accomplished via pain-staking calibration procedures. The manufacturer's quality control arrangements should, of course, identify and reject sensors with particularly large non-uniformities. However, for the purposes of image analysis, precise information with regard to picture element response would appear of paramount importance.
4.9 Summary

This chapter has detailed the experimental facilities, digital imaging and hot-wire anemometry equipment used to examine the wake flow behind a two-dimensional flat plate model. The wind tunnels and models used have been detailed and the physical configuration of the smoke flow visualization technique and digital imaging system discussed. The hot-wire anemometry equipment and the problems encountered in its use due to temperature fluctuations have also been outlined. Finally, a simple example of the steps involved in a typical image analysis routine have been outlined and the digital imaging assumptions and characteristics detailed.

The following chapter describes how these experimental facilities were employed in the present study, with particular reference being made to the comparable results obtained from the mutually exclusive digital imaging and hot-wire systems.
CHAPTER FIVE

EXPERIMENTAL MEASUREMENTS

5.1 Introduction

The review of previous work involving two-dimensional flat plate models (Chapter 2) illustrated those flow aspects that indicated it would be a suitable test model upon which to conduct an investigation of a digital imaging technique. In addition to the established data available from such literature, the influence of experimental factors such as freestream turbulence intensity and model length to breadth aspect ratio have been shown to produce considerable variability in experimental results. In view of this, any proposed experimental investigation of the digital imaging technique should also include the acquisition of directly comparable flow information (hot-wire anemometry in this case) to provide accurate data for the tunnel conditions and models used in this particular study. The experimental measurements undertaken for this study are presented in two sections, these being:

5.2 Preliminary Measurements

5.3 Comparative Wake Measurements

The preliminary measurements outlined in section 5.2 include such data as mean pressure distributions and a spanwise spatial correlation function to assess the two-dimensionality of the flow around the model. The mean near-wake, longitudinal-centreline static pressure distribution was also investigated to examine the vortex formation region with respect to the establishment of a 'Universal Strouhal Number', for which the transverse mean turbulence intensity distribution was also determined (at the isolated plate minimum wake centreline static pressure location).
Wake measurements of mean longitudinal velocities and turbulence intensities were also undertaken to assess whether the introduction of the small-bore smoke-tube and base-bleed required for the flow visualization study (detailed in section 4.6.2) unduly affected the quantifiable wake characteristics.

Section 5.3 outlines the wide range of directly comparable results that were obtained using both hot-wire anemometry and the digital imaging technique. The hot-wire experiments were arranged to simulate the smoke flow visualization studies through the introduction of a similar base-bleed rate (without the smoke) through the smoke-tube assembly. The individual sub-sections first introduce the flow characteristic to be compared and, outline how the results were determined using both hot-wire and digital imaging techniques, before describing the locations and flow conditions under which the measurements were performed. The flow characteristics compared in this manner are as follows:

5.3.1 Intermittency
5.3.2 Autocorrelation and Spectral Analysis
5.3.3 Spatial Correlation
5.3.4 Wake Interface Statistics
5.3.5 Mean Fluctuating Turbulence Quantities

The descriptions of the digital imaging flow analyses assume prior knowledge of the imaging equipment and its functioning (previously outlined in sections 3.4 and 4.5, respectively) and no further clarification of technical terms involved in the digital imaging technique are contained within this chapter. The graphical representation of the experimental results has adopted a consistent set of symbols throughout this dissertation, these symbols being as follows:

- Pressure Measurements
- Hot-Wire Measurements
- Digital Imaging Measurements
Unless otherwise stated, the measurements reported in this chapter were conducted in the smoke tunnel facility using the flat plate model having a breadth of 50.8mm, normal to the uniform flow direction. (Details of the smoke tunnel and flat plate model are to be found in sections 4.2 and 4.3, respectively). The majority of experiments reported have been undertaken at a Reynolds number of $1.36 \times 10^4$, corresponding to a freestream velocity of 4.0 m/s. Due to the frequency of reference to this particular Reynolds number, it has been given the descriptive title of 'test Reynolds number', so that:

'Test Reynolds Number' = $1.36 \times 10^4$

The comparative nature of this study has allowed the majority of measurements to be uncorrected for blockage effects, and unless specified to the contrary, should be treated as such. Due to the nature of the investigation no assumptions were made with regard to wake symmetry, necessitating the investigation of all measured flow characteristics across the entire wake region.

5.2 Preliminary Measurements

The following preliminary measurements were undertaken in order to examine the fundamental flow characteristics associated with the normal flat plate model in the smoke tunnel facility. Primarily, surface pressure measurements including the spanwise base pressure distribution and spanwise spatial correlation measurements were undertaken to establish the model drag coefficient, base pressure and the flow two-dimensionality, respectively. To facilitate the calculation of the Universal Strouhal Number ($St_\#$), vortex formation region characteristics such as the longitudinal-centreline static pressure coefficient distribution and transverse mean longitudinal turbulence intensity distribution (at the downstream location corresponding to the minimum static pressure) were measured. Finally, comparative wake measurements were undertaken with the
isolated flat plate, the plate with smoke-tube and the flat plate with smoke-tube and base-bleed. These latter measurements were conducted in order to establish whether the requisite smoke visualization apparatus was sufficiently unobtrusive so as not to unduly affect the isolated model's wake flow characteristics. An examination of these mean wake characteristics was undertaken through extensive hot-wire velocity and turbulence intensity investigations.

5.2.1 Surface Pressure Measurements

The mid-span pressure distribution on the upstream face of the isolated model was measured at the test Reynolds number and at a freestream velocity of 8.0 m/s, corresponding to a Reynolds number of $2.73 \times 10^4$ (Figure 13). The mean spanwise base pressure distribution was also recorded at the test Reynolds number, Figure 14, the base pressure being measured at 0.5 D intervals over the range 0.0 to 7.38 Z/D. The distributions are presented as non-dimensional pressure coefficients; $C_p = (p_s - p_o) / \frac{1}{2} \rho U^2$, where $p_s$ and $p_o$ are surface pressure and freestream static pressures, respectively.

5.2.2 Spanwise Spatial Correlation Measurements

The spanwise spatial correlation distribution in the near-wake of the isolated model was determined using two hot-wire probes at the test Reynolds number (Figure 15). One hot-wire sensor was fixed on the mid-span and centreline of the model, at a distance 2.0 X/D behind the plate, whilst the second hot-wire was traversed from very nearly the same location in a spanwise direction over the range 0.0 to 4.75 Z/D, at 0.25 D intervals. The definition of the spatial correlation function used is given in the more detailed comparative measurement section 5.3.3, later in this chapter. Unfortunately, the limited traversing facilities available to this study did not allow correlation factors to be acquired at spanwise distances greater than 4.5 Z/D, requiring the correlation function to be extrapolated to a zero value to calculate the integral length scale, $L_{uz}$. 
5.2.3 Vortex Formation Region Characteristics

The mean longitudinal wake static pressure distribution was measured at the test Reynolds number on the mid-span centre-line over the range 0.1 to 2.0 X/D, at 0.125 D intervals and from 2.0 to 4.25 X/D, at 0.25 D intervals (Figure 16). The distribution is presented as non-dimensional pressure coefficients in a similar manner to that defined in section 5.2.1. Rather than undertake disc-static probe corrections (section 4.4), the experimentally acquired values were corrected against the surface measured base pressure value.

The transverse mean longitudinal turbulence intensity \( \sqrt{\frac{u'^2}{U_0}} \), velocity, kurtosis and skewness distributions were established at the downstream location corresponding to the minimum pressure coefficient as identified by the longitudinal pressure distribution, at the test Reynolds number (1.125 X/D, mid-span). The traverse extended from -2.5 to +2.5 Y/D, at 0.125 D intervals (Figures 17a to d). These distributions were established for the isolated plate only, to provide information for the calculation of the Universal Strouhal Number, \( St^* \).

5.2.4 Mean Velocities and Turbulence Intensities

Measurements of the normalised mean longitudinal velocity \( \bar{U}/U_0 \) and turbulence intensity \( \sqrt{u'^2}/U_0 \) were taken in the near-wake of the flat plate using a single hot-wire anemometer at Reynolds numbers of 6.82 \( \times \) 10\(^3\), corresponding to a freestream velocity of 2.0 m/s, and at the test Reynolds number (mid-span plane), Figures 18a to f. The quantities were measured over traverses extending from -5.0 to +5.0 Y/D, at 0.125 D intervals and at downstream locations between 2.0 and 12.0 X/D, at 2.0 D intervals. The traversing grid was repeated for:

(i) the isolated plate,
(ii) the plate with smoke-tube, and
(iii) the plate, smoke-tube with base-bleed.
A wake centreline traverse was also undertaken from 0.3 to 12.0 X/D, at 0.25 D intervals, the mean longitudinal velocity and turbulence intensity distributions being shown in Figures 19a and b.

5.3 Comparative Wake Measurements

This section outlines a series of wake measurements conducted on the flat plate model using both hot-wire anemometry and the digital imaging technique. The hot-wire experiments were arranged to simulate the flow visualization studies by the introduction of an identical base-bleed rate into the plate wake through the smoke-tube assembly (without the smoke). All measurements were undertaken at the mid-span plane (0.0 Z/D) of the model and, unless otherwise stated, were conducted at the 'test Reynolds number' of 1.36 \( \times 10^4 \), corresponding to a freestream velocity of 4.0 m/s. With the exception of the spatial correlation investigations (referred to in detail later in section 5.3.3), the following comparative digital imaging studies have been undertaken with the seeded flow illuminated by a transverse single beam as shown below:
A preliminary study of constant illumination and continuously varying background scenes using the statistical attributes of the real-time digital imaging system (described in detail in section 5.3.5), identified specific 'lines' of the image sensor within which non-uniformities or 'dead' pixels were present. Due to the single line nature of the quantitative imaging techniques, it was generally possible to avoid these imperfect sensor lines and, where possible, one specific line of the sensor was used repeatedly to reduce sensor-induced variability at different downstream locations. Where feasible, the complete experimental results of both the hot-wire and digital imaging techniques have been presented so as not to unduly influence the comparative nature of this dissertation by the artificial 'smoothing' of experimentally achieved distributions.

Each of the following sub-sections in this section deals with a specific aspect of the comparative study and following an introductory discussion, outlines in detail the experimental measurements undertaken in the following order:

(a) hot-wire anemometry, and

(b) digital imaging technique, and

(c) locations of flow conditions for measurements in question.

The computational imaging routines described within these sub-sections are, as far as possible, illustrated as annotated examples. It must also be recognised that although each of these imaging technique characteristics has been treated as independent analyses, all of these routines (with the exception of the spatial correlation function) may be simultaneously undertaken from a single, experimental study and do not require independent experiments. This may not appear immediately obvious from these measurement details as each aspect of this comparative study has been independently treated as a separate topic.
5.3.1 Intermittency Measurements

The concept of intermittency may be simply explained by considering that if a particular flow location is examined, the fraction of the total time that the flow at that point is 'turbulent' is called the 'intermittency factor', $\mathcal{V}$, where the intermittency function $I(x,t)$ is defined by:

$$I(x,t) = \begin{cases} 
1 & \text{if the point } (x,t) \text{ is in a turbulent region} \\
0 & \text{if the point } (x,t) \text{ is in a non-turbulent region}
\end{cases}$$

Intermittency is an important statistical characteristic of wake flows, and in order to study properties connected solely with the turbulent or non-turbulent flow regions, it is necessary to consider some form of intermittency or turbulence detector. Quantities such as the turbulent energy and turbulent shear stress, for example, are small or zero in the irrotational flow and it is therefore necessary to divide mean measured quantities by the intermittency factor at the considered location to obtain the average values relevant to the turbulent fluid contribution. Direct incorporation of a turbulence or intermittency detector also allows the direct evaluation of turbulent and non-turbulent zone averages as independent statistical sets. Intermittency detection using velocity signals and passive scalars has been previously reviewed in section 2.3, and alternative means of intermittency analysis will not be discussed further in this particular section.

Ideally, the condition for a flow to be defined as turbulent or not, would involve the determination of the variance of the vorticity fluctuations. Experimentally, this is not easily obtainable, and a simplified discriminator, such as velocity fluctuations is more often employed. In practice, a signal is generally emitted by a discriminator circuit which responds only if a differentiated hot-wire signal has a magnitude greater than a specified (frequently arbitrary) threshold level within a short time interval, sometimes referred to as a 'memory' time. Passive scalars such as
smoke should simplify the discriminator used to detect turbulence as, if the scalar is introduced into the turbulent flow only and remains there, any subsequently detected scalar traces may be associated with a turbulent flow region. This, of course, is only a simplified view of a complex problem, which as previously mentioned, has been reviewed in more detail in section 2.3.

(a) Hot-Wire Intermittency Detection

An analogue circuit to detect turbulence and produce an intermittency factor was not available for this study. Construction of the necessary circuitry was considered, but although the analogue components would have been relatively uncomplicated, the low electrical noise requirements of such a circuit would have required a great deal of careful design and painstaking development. Operational time requirements, therefore, did not allow the necessary analogue design, and an alternative high-speed digital sampling detector system was relatively quickly developed.

The digital detector system calculated the turbulence intensity of a number of successive velocity measurements. If the calculated intensity exceeded a programmable threshold, the central sample value of the considered velocity measurements was considered to be 'turbulent', if not, it was 'non-turbulent'. The acquisition rate, number of successive velocity measurements to be considered for each decision, and the aforementioned threshold level could all be individually programmed.

The definition of the turbulence detector level, $T_c$, may be expressed as:

$$T_c = \frac{\sum \sqrt{\bar{u}^2}}{U_o}$$  

> Threshold = turbulent, otherwise, non-turbulent.

where $u$ is a sampled velocity.
Throughout the reported hot-wire intermittency experiments, three successive velocity samples were acquired at a sampling rate of 5 kHz. A total sample population of 50,000 velocities ensured an intermittency factor repeatability of less than plus or minus two percent in fully turbulent and intermittent flows. In order to enable a high-speed, continuous sampling rate, the programme used to calculate the intermittency factor first stored the velocity samples directly to computer memory, and then calculated the necessary turbulence values as a post-processing routine.

Figure 20 shows the freestream characteristic intermittency factors obtained at the test Reynolds number, $2.73 \times 10^4$, and $3.85 \times 10^4$, corresponding to freestream velocities of 8.0 and 11.3 m/s, using varying turbulence detection threshold levels. Signal noise was a continual source of possible system error, requiring great care in component location and signal earth protection to ensure a minimal level of air-borne and inductive interference. A turbulence threshold level of 0.2 percent was used throughout the intermittency experiments, this proving to be the approximate level of longitudinal freestream turbulence intensity within the undisturbed freestream. As indicated in Figure 20, this value was extrapolated from the freestream data and, throughout the velocity range considered, possessed a finite and variable (depending on Reynolds number) contribution of signal noise, causing a freestream intermittency factor marginally exceeding the theoretical factor of zero. The turbulence threshold level was, however, considered to be independent of Reynolds number, although due to the operating mode of the hot-wire anemometer, higher Reynolds numbers produced an anemometer signal with a relatively increased signal-to-noise ratio, improving the intermittency factor accuracy and producing an irrotational flow intermittency factor closer to the theoretical zero value. The intermittency results discussions (sections 6.3.1 and also 6.3.4) will later reveal that the adoption of a constant threshold level across the wake may not, in fact, have been strictly correct.
Having established a successful intermittency indicator, it was possible to calculate 'zonal' averages for a sample of streamwise velocity components, enabling independent turbulent and non-turbulent zone statistics to be calculated. Accordingly, the hot-wire intermittency analysis programme grouped the acquired velocity components into turbulent and non-turbulent parts and calculated the corresponding turbulent and non-turbulent mean longitudinal velocity ($\bar{U}/U_0$) and turbulence intensity ($\sqrt{\bar{u}^2/U_0}$). In a similar manner to that described in section 4.5.2 for the standard 'combined' hot-wire measurements the probability density distribution moments of both zoned velocity components were also calculated. Figures 21a and b show the measured turbulent, non-turbulent and standard combined zone velocity and turbulence intensity distributions at a downstream location of 12.0 X/D, at the test Reynolds number. The square-root of the non-turbulent turbulence intensity has also been plotted against transverse distance for downstream locations between 2.0 and 12.0 X/D, at 2.0 D intervals (Figures 22a to f), again at the test Reynolds number.

(b) Digital Imaging Intermittency Detection

Having made the basic assumption that a smoke contaminant introduced into a wake is effectively confined to the turbulent regions of the flow (see section 4.8.1), the definition of the detection criterion for turbulence becomes extremely uncomplicated. Examining a single location in a flow, it may be assumed that if smoke is detected at this point, then at that instant in time the location under consideration is within a turbulent flow region. Similarly, if no smoke is observed, that location is within a non-turbulent region. Unlike the use of heat as a passive flow contaminant, there is no residual smoke present in the freestream or irrotational flow (assuming effective system filtration) inferring that spurious 'freestream' smoke detections outside of the turbulent wake should not be possible.
Digitisation of the visualized wake video image typically provided a maximum of three lines of significant digital information (dependent on the focal length of the lens used), with 512 individual pixel locations per line. A single line of the image was selected and analysed in real-time, and a record of each pixel's state on that line at each inspection was cumulated in a storage array within the PDP11/73 RAM. The digital imaging intermittency analysis procedure may be demonstrated by the following graphical representation.
The analysis of the pixel locations required no account of an individual pixel's intensity value, but merely inspected its 'on' or 'off' state. A value of zero indicated the pixel was 'non-turbulent', whilst any other value indicated that the pixel was 'turbulent'. A typical analysis involved 5,000 to 20,000 fields in real-time, which corresponded to 100 to 400 seconds of data acquisition. The signal-to-noise ratio of the video source with respect to the bit digitisation level has been previously discussed in section 3.2, and signal noise was, on occasion, the cause of spurious pixel illuminations. Fluctuations in camera 'dark' current or 'black' values could also cause false pixel indications. Using the solid state CCD video camera, digitised to six bits and continuously force-cooled, these noise contributions were, however, practically non-existent. A standard raster-scan type video camera would not only possess a lower signal-to-noise ratio but would also trigger more false pixel indications due to greater fluctuations in the dark current level. It would, therefore, prove far more difficult to apply a standard raster-scan type camera source to this particular digital imaging application.

The intermittency function obtained by the video analysis technique has been designated the descriptive title of 'pixel intermittency function'.

(c) Intermittency Measurement Details

Hot-wire and pixel intermittency functions were obtained for the test Reynolds number at downstream locations between 2.0 and 12.0 X/D, at 2.0 D intervals (Figures 23a to f). The hot-wire intermittencies were determined over the range -5.0 to +5.0 Y/D, at 0.25 D intervals. Additional comparative results were obtained for alternative Reynolds numbers of 2.05 \times 10^4 and 2.73 \times 10^4, corresponding to 6.0 and 8.0 m/s at a downstream location of 6.0 X/D (Figures 24 and 25). Figure 26 shows an iso-intermittency contour map obtained via the digital imaging technique for downstream locations between 2.0 and 12.0 X/D, at the test Reynolds number.
5.3.2 Autocorrelation Function and Spectral Analyses

Time-dependent fluctuations of a measured quantity may be analysed using the autocorrelation function, defined as:

\[
R(T) = \frac{\lim_{T \to \infty} \int f(t) f(t+T) \, dt}{\lim_{T \to \infty} \int f(t) f(t) \, dt}
\]

where \( R(T) \) is the autocorrelation factor, and \( T \) is a time interval or lag. The number and duration of the time lags determines the accuracy of the autocorrelation function with respect to a subsequent spectral analysis. To accurately define source signal frequencies, an autocorrelation function should ideally be calculated over sufficient time lags to allow the function to decay to zero. In practice, this may demand the calculation of an excessive number of lags, and in general, a finite number of lags may be calculated to produce a limited autocorrelation function. Having established this limited or truncated function, analytical extrapolation procedures may, if desired, be invoked to produce a fully decayed function. Stone (1978) presented both extrapolation and interpolation procedures for autocorrelation functions, which were based on the statistical properties of the autocorrelation matrix, although other extrapolation procedures are also available. A frequency domain or spectral analysis may then be computed from the autocorrelation function to determine the various frequency components of the source signal. The spectral energy of a given frequency 'n' may be calculated by the Fourier cosine analysis, defined as:

\[
E(n) = 4 \int_0^\infty R(T) \cos 2\pi n T \, dT
\]

where \( E(n) \) is the spectral energy of the frequency \( n \).

The Fast Fourier Transform (FFT) also allows the digital calculation of a power spectral analysis directly from a raw input signal. Although slower and not regarded as 'state-of-the-art', the autocorrelation function, Fourier cosine analysis combination was preferred for this
particular application to an alternative 'high-performance' FFT method. The primary reason for this preference was that the autocorrelation function provided a visible description of frequency fluctuations which may lead to a clearer perception of a fluctuating phenomenon. Having calculated the autocorrelation function the Fourier cosine analysis may be repeated a number of times, using the same autocorrelation input function, to provide analyses over different frequency ranges with variable degrees of precision. In this manner, frequencies of interest may be examined in detail using an accurate, so-called narrow-band analysis. An FFT routine, on the other hand, is restricted to analyses at specific frequencies (depending on the sampling rate and size), which although offering an expedient analysis technique, does not offer a great deal of useful flexibility, especially when the input sampling frequency is fixed (as in the case of the digital imaging system).

Experimentally, the frequencies being detected were the shedding frequencies of the large-scale, so-called Strouhal vortices. Spectral analyses of these vortices were performed using both hot-wire anemometry and image analysis techniques.

(a) Hot-Wire Spectral Analysis

It is generally possible to detect vortex shedding frequencies using hot-wire probes across the entire extent of a bluff body wake. Over the central region of the wake, twice the shedding frequency may be detected due to the influence of the alternately shedding vortices. The signals from a probe situated within the wake are, however, complicated by broad frequency turbulence fluctuations and passive signal filters should be incorporated to yield any conclusive results. The most satisfactory location for an unfiltered hot-wire probe to detect vortex shedding is, therefore, outside the turbulent wake. Potential motions induced in the irrotational flow by the wake vortices appear
as near sinusoidal anemometer signal fluctuations and provide an uncomplicated, yet precise indication of the vortex shedding frequency. This technique was extensively employed by Fage and Johansen (1927a) and was also adopted for these tests.

Vortex shedding frequencies were established with the hot-wire probe located outside the turbulent wake at a downstream location of 2.0 X/D, this being the approximate location of the vortex formation region and where the induced velocity fluctuations were found to be most pronounced. The signal from the anemometer was monitored and the transverse location of the probe adjusted until no short-duration bursts of 'turbulent' signal fluctuations were detected. By far the most common means of ensuring such a probe location is to observe the anemometer signal on an oscilloscope, although the PDP11/73 hot-wire programme suite could also be used to observe the velocity signal flatness factor, which has a high value on the 'intermittent wake edge' and a value near 3.0 within purely irrotational flow. This transverse location was generally found to be approximately 2.0 Y/D from the wake centreline for the flat plate model under consideration. The sampling frequency of the Analogue to Digital Converter board was controlled by an externally applied variable digital frequency source, and could be varied over the range 1 to 25,000 Hz, at specific frequency increments. Typical sample populations of 5,000 velocities were sufficient to ensure an accurate mean shedding frequency analysis. Larger sample populations could have been acquired but were found to be unnecessary for the shedding frequencies encountered in this study. In order to allow continuous sampling at the higher sampling rates (>5,000 Hz) the autocorrelation and spectral analyses were performed as post-processing functions, requiring approximately three minutes of computer processing time. The sampling rates used in this particular study were 61.0 Hz and 242.2 Hz (at these relatively low sampling rates it would also have been possible to implement an on-line autocorrelation function analysis).
(b) **Digital Imaging Spectral Analysis**

Two distinct digital imaging analysis techniques were used to determine the vortex shedding frequencies of the turbulent wakes. Both techniques were limited to an upper detection frequency of 25 Hz, this being half of the sampling frequency or 'Nyquist' frequency, imposed by the field rate (50 Hz) of the video system. The two autocorrelation techniques used operated on:

(i) wake interface detection, and

(ii) pixel intensity fluctuations.

The primary digital imaging technique detected the sequential locations of the outer smoke/no-smoke interface. The interface location had the form of an integer offset between the values of 0 and 511 corresponding to the pixel location relative to the image edge. A suitable camera lens was used to facilitate visualization of the entire wake width, allowing the determination of both 'left' and 'right' interface locations. Edge detection consisted of acquiring a single line of digitised video data as a 512 byte array. The so-called 'left-hand edge' was located by incrementing through the array until three successive non-zero values were encountered (the background 'non-turbulent' light intensity value being zero, indicating a black image). The 'right-hand edge' was located by decrementing through the array from the last array location until detection as previously described. It was felt necessary to detect an edge after three 'positive' pixel encounters to ensure that spurious 'odd' pixel illuminations did not cause false edge detection triggering. More elaborate edge detection algorithms were initially rejected due to the timing constraints imposed by the real-time analysis requirements. A sample population of between 5,000 and 30,000 edge locations was available, although most experiments were restricted to 5,000 field acquisitions to maintain a reasonably short (100 seconds) experimental sampling period.
Autocorrelation and spectral analyses were generally performed as post-processing functions.

A high-speed version of the above-outlined detection method was capable of performing a 'left' edge detection only plus calculate a continuous 100 lag autocorrelation function in real-time. Subsequent spectral analyses provided an efficient 'short-form' shedding frequency analysis, requiring a minimum of processing for an 'instant analysis'.

The digital imaging autocorrelation edge-detection procedure described above may be demonstrated by the graphical representation shown below.

![Graphical representation of autocorrelation and spectral analyses](image-url)
The edge detection method of spectral analysis provided information concerning the frequency characteristics of the smoke/no-smoke interface. To examine the frequency characteristics across the entire illuminated turbulent wake a second spectral analysis method was adopted, which involved storing successive light intensity values from 25 individual pixel locations along the illuminated wake beam. (The 25 pixel locations were initially programmed, using a variable first pixel location with a specified pixel separation). In this application it was necessary to utilise the second imaging frame buffer as a high-speed memory store, allowing the storage of 10,000 lines of information in 250 kilobytes of directly addressable memory. Post-processing involved the calculation of 25 independent autocorrelation functions from the digitised records of the light intensity fluctuations at each particular pixel location and corresponding spectral analyses, the majority of which were undertaken using the PDP11/73 batch processor. (If a batch processor had not been available, spectral analyses via an FFT function would most certainly have been implemented in order to reduce the processing demands placed on the host). Whilst the results of the pixel autocorrelation procedure are similar in format to those previously sketched, the acquisition of the individual pixel values may be regarded as the simultaneous formation of 25 individual integer arrays, each typically containing 10,000 sequential pixel values.

(c) Spectral Analysis Measurement Details

Hot-wire and digital imaging autocorrelation analyses using the edge detection method were conducted on the normal flat plate wake over a Reynolds number range of \(6.82 \times 10^3\) to \(2.73 \times 10^4\), corresponding to freestream velocities between 2.0 and 8.0 m/s (Figures 27a to 28d). (As neither method detected a change in shedding frequency with downstream distance, comparative results were obtained at a single downstream location of 2.0 X/D). The hot-wire sampling frequency derived from the fixed frequency source was
operated at 244.2 Hz and 61.0 Hz, the former frequency being used to provide accurate autocorrelation functions with a Nyquist frequency of 122.1 Hz, whilst the latter frequency was selected to be as close to the 50 Hz sampling rate of the digital imaging equipment as was achievable with the available digital frequency source. Figures 27a to d show the auto-correlation functions and spectral analyses achieved with the digital imaging technique, whilst Figures 28a to d are comparisons of the hot-wire autocorrelation functions and spectral analyses achieved at the two previously mentioned sampling frequencies. Figure 29 shows the shedding frequency dependency on Reynolds number as indicated by both methods and Figure 30 depicts the corresponding Strouhal number relationship.

The pixel intensity fluctuations within the wake region were analysed at the test Reynolds number, Figure 31 showing the spectral intensity distribution of the principal shedding frequencies detected in the half-wake of the flat plate, the distributions being at 2.0, 4.0, 8.0 and 12.0 X/D. Figure 32 shows the corresponding unfiltered hot-wire anemometer spectral intensity distribution of the principal shedding frequencies across the half-wake at a downstream location of 6.0 X/D (sampling frequency 244.2 Hz). Additional comparative results were obtained via the edge detection and hot-wire autocorrelation analyses with the flat plate at various angles of incidence to the freestream. Figures 33a to g show the autocorrelation functions and spectral analyses achieved with the digital imaging technique for the flat plate at angles of incidence of between 90 and 30 degrees to the freestream, at 10 degree intervals. Figures 34a to g show the autocorrelation functions and spectral analyses obtained by the hot-wire anemometer (sampling frequencies of 244.2 Hz and 61.0 Hz) over the same range of incidence angles. Figure 35 shows the shedding frequencies detected using both of the afore-mentioned methods over angles between 90 and 30 degrees to the freestream at the test Reynolds number, whilst Figure 36 depicts the corresponding Strouhal number relationship.
5.3.3 Spatial Correlation

In order to obtain length scales of a fluctuating motion it is important to study the correlation between the same fluctuating quantity measured simultaneously at two different points in space. The spatial correlation coefficient may be defined as:

\[ R(r_1, r_2, r_3) = \frac{u(x) u(x+r)}{u^2(x)} \]

where \( R(r_1, r_2, r_3) \) is the spatial correlation coefficient and 'r' is the separation distance between the measurement points.

The dimensionless integral length scale \( L(x) \) of the spatial correlation function is defined as:

\[ L(x) = \int_0^\infty R(x) \, dx . \]

The spatial correlation experiments were conducted principally to establish the streamwise separation of the Strouhal vortices in the turbulent wake. In order to measure vortex separation, the distance between the positive peaks of the correlation function may normally be measured (indicating that the fluctuations at that separation are in phase). Spatial correlation functions were established using both hot-wire anemometry and the digital imaging technique.

(a) Hot-Wire Spatial Correlation

Hot-wire spatial correlation was achieved by correlating the fluctuating velocities of two unfiltered hot-wire probes separated by a given distance. Correlation was digitally established from the two independently acquired digital velocity values, the spatial dimensions determined being the streamwise separation distances between wake vortices. In practice this required one hot-wire to be fixed at some location and another probe to be traversed downstream from the first. Attempts to measure the longitudinal vortex
spacing ratio with both probes situated within the wake were found to be unreliable and produced unrealistic functions. In these experiments the fixed probe had been located within the vortex formation region where the velocity signals were highly turbulent and complicated by flow reversals. In addition, a degree of probe interference must inevitably occur with two probes aligned in the wake, even after an allowance of small offsets as used by many experimenters. To overcome these difficulties and remove the possibility of probe interference, a method of spatial correlation measurement first reported by Fage and Johansen (1927a) was adopted. Unfortunately the traversing requirements of this method were beyond the capabilities of either of the available smoke tunnel traversing units and alternative experiments were therefore conducted in the larger boundary layer tunnel using its computer-controlled traversing facilities (previously outlined in section 4.2).

The hot-wire spatial correlation procedure consisted of locating the two hot-wire probes outside the turbulent wake in the irrotational flow, in a manner similar to that described in section 5.3.2 (with regard to autocorrelation). The fixed wire was located at 2.0 X/D corresponding to the approximate location of the vortex formation region. The spatial correlation function was then determined by traversing the second wire downstream outside the wake (on the opposite side) as indicated by the following sketch.
Digital imaging spatial correlation was achieved by correlating the fluctuating pixel intensities at different locations in the image. To study the longitudinal spatial characteristics of the wake, the illuminating laser beam was reflected by an optical mirror along a streamwise path having a transverse location of approximately 1.5 $Y/D$. The arrangement illuminated a bar of light, which exited the seeded wake within the vortex formation region as indicated below:

```
Smoke-Seeded Wake

Silver-Faced Mirror

Laser Beam
```

**FLAT PLATE SPATIAL CORRELATION ILLUMINATION**

The camera was arranged so that the illuminated beam coincided with one line of the digitised image (as with all of the other transverse measurements) and in order to avoid as much of the previously mentioned image distortion, this line was chosen to be approximately the middle line of the image sensor (line 128 for a 256 line image). The pixel intensity at a pixel location at one end of the line was then correlated in real-time with all of the other pixel intensities on that line to produce a 'pixel correlation function'. The pixel locations were then transformed to physical dimensions via the previously determined pixel-to-distance calibration results to form the spatial correlation function.
The digital imaging spatial correlation procedure described above may be demonstrated by the graphical representation shown below.

Detail A

Detail B

Detail C

Field No. 1

Field No. 2

Field No. 3

Pixel No. 1 2 3 4 5 6 7 8 9 10

Detail A 90 77 65 60 79 94 89 71 43 21

Detail B 88 90 11 25 49 52 31 68 80 99

Detail C 52 57 73 82 87 98 76 65 63 53

Pixel Separation

Pixel Correlation
The illuminated bar was viewed using either a wide angle (8.5mm focal length) or 'fish eye' (4.8mm focal length) camera lens, enabling the entire length of the beam to be simultaneously digitised. The 4.8mm lens, and to a lesser extent the 8.5mm lens, caused some geometrical distortion of the visualized image which was accounted for by a pixel location calibration against a metred object. The sketch below illustrates typical 'fish-eye lens' image distortion.

Original Shape  
\[ 
\begin{array}{ccccc}
\hline
& & & & \\
\hline
& & & & \\
\hline
& & & & \\
\hline
\end{array}
\]

'Fisheye' Lens Distorted Image

\[ 
\begin{array}{ccccc}
\hline
& & & & \\
\hline
& & & & \\
\hline
& & & & \\
\hline
\end{array}
\]

An alternative form of the digital imaging spatial correlation function was calculated by ignoring the absolute values of the individual pixel intensities along the illuminated line and instead, using values of 0 or 1 for that pixel location depending on whether the pixel had an intensity value of 0 or not, i.e.

\[
\text{Pixel Value} = \begin{cases} 
1 & \text{If the original pixel intensity is } > 0 \\
0 & \text{If the original pixel intensity is } = 0 
\end{cases}
\]

From the previous description in section 5.3.1, it may be observed that this 'on' or 'off' calculation produced a 'spatial intermittency' correlation function, the correlation being an indication of the relationship between vortices as entire structures (or 'blobs') rather than their inner details.
The hot-wire spatial correlation was conducted on the normal 30.0mm flat plate model in the boundary layer tunnel at an equivalent test Reynolds number of $1.36 \times 10^4$, corresponding to a freestream velocity of 6.75 m/s (Figure 37). Comparative digital imaging spatial correlation functions were obtained in the smoke tunnel with the normal flat plate at Reynolds number of $6.82 \times 10^3$, 1.36 and $2.73 \times 10^4$, corresponding to freestream velocities of 2.0, 4.0 and 8.0 m/s (Figure 38), and using a different camera position and focal length lens at Reynolds numbers of $6.82 \times 10^3$ and $2.05 \times 10^4$, corresponding to freestream velocities of 2.0 and 6.0 m/s (Figure 39). Comparative imaging spatial correlations were also undertaken at the test Reynolds number with varying degrees of image blur, corresponding to image integration periods of 20, 16 and 8 mS, Figure 40.

Additional digital imaging spatial and 'spatial intermittency' correlations were subsequently obtained at the test Reynolds number with the flat plate model at various angles of incidence to the freestream direction. Figures 41a to g show the spatial and 'spatial intermittency' correlation functions obtained at angles of 90 to 30 degrees to the freestream, at 10 degree intervals.

5.3.4 Wake Interface Statistics

In order to reveal the shape and motion characteristics of the turbulent/non-turbulent interface in a wake flow it is necessary to establish descriptive statistical values. The determination of an intermittency detector incorporates a turbulence discriminator and has been discussed in some detail in section 5.3.1. Having established some form of discriminating criterion, if the output from the intermittency device changes state from 'non-turbulent' to 'turbulent' or vica versa, then the interface between the two states of flow must have been encountered.
If a single point sensor is used, an interface may only be sensed as it is swept past the probe. An array of hot-wires would provide more chances of detecting the interface location and may lead to the additional possibility of calculating the transverse interface velocity. Unfortunately, an 'array rake' of hot-wires was not available for this study (the hardware requirement would possibly be prohibitive to a majority of experimenters). Using a smoke visualization technique, however, every time an illuminated image is examined the smoke/no-smoke interface locations (outer and inner) may be detected and stored.

(a) **Hot-Wire Interface Statistics**

If the output state from an intermittency detector changes from 'non-turbulent' to 'turbulent' a 'front' wake interface is said to have been encountered. Similarly, 'turbulent' to 'non-turbulent' indicates a 'back' interface. In addition to the outer-edge intermittency of a wake, the process of vortex roll-up entrains non-turbulent fluid into the wake and inner short-duration interface encounters may also occur. The relative accuracy of the interface detection (especially with respect to these inner edges) is a combination of the respective accuracies of the turbulence detector and interface discriminator used. The number of interface crossings encountered at each transverse wake location over a given period may be combined to form a so-called 'crossing frequency function'.

(b) **Digital Imaging Interface Statistics**

As described in section 5.3.2, the autocorrelation function was determined by the establishment of the outer smoke/no-smoke interface. The location of the outer interface may be detected for every visualized image (unlike the hot-wire probe that must wait for the interface to be swept past its fixed position). The digital imaging technique, therefore, provides a direct record of the movement of the outer
interface with respect to time. The time-averaged distribution of these outer interface locations was analysed directly from the 'autocorrelation interface' data, termed the 'outer interface probability distribution function'. A further assumption was made with regard to outer interface motion which allowed the calculation of the transverse wake interface velocity. This assumption stated that the transverse component of the interface could be established from the fixed timing interval between fields and the pixel separation distance between two successive interface locations. The 50 Hz sampling rate of the video camera was too slow to entirely validate this assumption and errors due to interface velocity fluctuations and direction reversals should be expected. The relatively 'slow' sampling rate of the imaging system also dictated that a more in-depth study of vortex motion could not be undertaken, a vortex shedding frequency of 12 Hz yielding 4 individual visualizations per shed vortex. To study the shedding mechanism in detail, it would be desirable to obtain at least 20 visualizations per vortex, necessitating a sampling frequency in the region of 240 Hz, for which high-speed photography or linear CCD array devices would undoubtedly have been more suitable.

In addition to the outer edge interface statistics, the digital imaging technique also provided an opportunity to quantify certain characteristics of the interfaces detected 'within' the main turbulent flow regime. The 'inner' interface assumption relied on the smoke/no-smoke boundary indicating where regions of non-turbulent fluid were present 'within' the turbulent flow, these regions being assumed to be irrotational fluid in the process of being entrained. A schematic diagram of the various interface definitions is shown below.

'Outer Interface'                      'Outer Interface'

 'Inner Interfaces' (Interface Pair)
The digital imaging analysis routine sampled the digitised image and identified the outer interface locations of the wake in a similar manner to that previously described in section 5.3.2. Having established the wake extremity locations, the pixels between these locations were examined and the relative occurrences of any inner edges stored to an appropriate array. To avoid spurious pixel illuminations being erroneously classified as inner edges, the detection of a valid edge was again specified by the presence of at least three consecutive 'turbulent' pixels. The probability distribution of the combined inner and outer edge locations should provide a directly comparable interface probability distribution with the hot-wire probe crossing frequency (provided that both systems correctly identify all of the turbulent/non-turbulent interfaces). The distribution function of the combined inner and outer interface locations has been termed the 'ensemble interface distribution'. Having established the inner interface locations, it was also possible to determine the number of interface pairs encountered per image (i.e. the number of non-turbulent regions, each region having two interfaces), the time-averaged distribution of the number of interface pairs being termed the 'multi-valued interface distribution'.

A further function that may be calculated was the number and location of 'non-turbulent' pixels 'within' the turbulent flow region. This facility allowed the digital imaging technique to produce an 'intermittency' distribution of the non-turbulent flow 'within' the turbulent flow boundaries. A single hot-wire probe is not capable of providing such information as the precise locations of the turbulent/non-turbulent outer interfaces would be a pre-requisite to any decision. (Hot-wire determinations of this function could, however, be achieved using a rake of hot-wire sensors or by combining a simultaneous high-speed photographic flow visualization technique with a single flow sensor). The digital imaging function has been termed the 'non-turbulent intermittency distribution' and should not be confused with the 'simple' non-turbulent intermittency distribution that
could be calculated from the standard intermittency function, \((1-Y)\). The imaging interface statistics compilation methods may be illustrated by the following sketch.

Field No. 1

Field No. 2

Field No. 3

<table>
<thead>
<tr>
<th>Field No.</th>
<th>Left Edge</th>
<th>Right Edge</th>
<th>Interfaces</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>140</td>
<td>460</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>64</td>
<td>421</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>127</td>
<td>381</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>228</td>
<td>400</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>98</td>
<td>410</td>
<td>7</td>
</tr>
<tr>
<td>6</td>
<td>57</td>
<td>431</td>
<td>3</td>
</tr>
</tbody>
</table>

Left Edge Positive

Right Edge Positive

Probability Distribution

\(\Delta\) Distribution
Comparative digital imaging 'outer interface', 'ensemble interface' and hot-wire crossing frequency distributions at a downstream location of 6.0 X/D are shown for the test Reynolds number, Figure 42, and an additional Reynolds number of $2.73 \times 10^4$, corresponding to a freestream velocity of 8.0 m/s, Figure 43. Digital imaging 'outer interface' and 'ensemble interface' distributions at the test Reynolds number were achieved at downstream locations between 2.0 and 10.0 X/D, at 2.0 D intervals (Figures 44a to e), whilst Figure 45a shows the 'interface multi-valuedness distribution functions' achieved over the same downstream range and Figure 45b shows the cumulated multi-valuedness function for 6.0 and 10.0 X/D locations. The above digital imaging interface distributions are presented as 'smoothed' functions, an average distribution being taken from the experimental results.

Figures 46a and 46b show the 'raw' experimental detail of the 'left' and 'right' digital imaging 'outer interface' distributions achieved with sample populations of 5,000 and 40,000, respectively, at a downstream location of 6.0 X/D, test Reynolds number. Figures 47a and 47b show cumulated versions of the above 'left' and 'right' outer interface distributions at the test Reynolds number and at $2.73 \times 10^4$, corresponding to a freestream velocity of 8.0 m/s, again at 6.0 X/D. Figures 48a to f, show the experimental 'left' and 'right' digital imaging 'outer interface' distributions (5000 samples) from 2.0 to 12.0 X/D, at 2.0 D intervals. Figure 49a shows the mean 'outer interface' locations at the test Reynolds number from 2.0 to 12.0 X/D, at 2.0 D intervals, and also at a Reynolds number of $6.82 \times 10^3$, corresponding to a freestream velocity of 2.0 m/s, from 3.0 to 11.0 X/D, at 2.0 D intervals. Figures 49b, c and d depict the variance, skewness and kurtosis, respectively, of these independent 'left' and 'right' interface distributions at the test Reynolds number over the identical range of 2.0 to 12.0 X/D, at 2.0 D intervals.
Digital imaging interface velocity and acceleration distributions (Figures 54a to c) are shown in terms of pixel distances for downstream locations 2.0, 6.0 and 10.0 X/D, whilst Figures 55a to c depict the variance, skewness and kurtosis of these distributions, respectively.

Pixel intermittency and 'non-turbulent' intermittency functions at the test Reynolds number are also presented for downstream locations of 2.0 to 10.0 X/D, at 2.0 D intervals (Figures 56a to e), with Figure 57 showing the distribution of 'non-turbulent' intermittency integral expressed as a percentage of the turbulent intermittency function.

5.3.5 Mean Fluctuating Turbulence Quantities

A velocity sensing probe may or may not be capable of measuring either an instantaneous flow velocity component or both flow velocity and direction. Assuming that only a flow velocity component may be sensed, time-averaging the instantaneous velocities will provide a mean value of velocity component. The root-mean-square (r.m.s.) of the velocity fluctuations about the mean value, averaged over a given time, provides a measure of the fluctuating velocity component. This value may be normalised by the mean velocity component to produce a measure of turbulence intensity which may either be expressed as a decimal value or percentage. In a similar manner, a fluctuating signal such as the light intensity of a location within a visualized image may be time-averaged and its fluctuating component calculated. In order to avoid confusion, turbulence intensity refers to the normalised r.m.s. velocity fluctuations, whilst light intensity in this context is an instantaneous value of a particular illuminated picture element. To avoid possible ambiguities in terms, r.m.s. light intensity fluctuations are described as 'r.m.s. pixel intensities'.
(a) Hot-Wire Flow Measurements

Longitudinal velocity components and turbulence intensities were calculated at every hot-wire probe sampling location. In addition, the third and fourth order moments (skewness and flatness factor respectively) of the velocity components were also calculated from the sampled data. These statistical values are useful when comparing the probability distribution function of a velocity signal with that of a Gaussian probability distribution (see section 4.5.2). A value often used to directly compare the flatness factor with the expected value of three (previously derived in section 4.5.2) is 'kurtosis', equal simply to the flatness factor minus three. Higher order comparisons are also possible in this respect but were not used for this study.

(b) Digital Imaging Flow Measurements

The digital imaging technique allowed time-averaged light intensity distributions and r.m.s. pixel intensity distributions to be acquired in real-time over the entire wake width (at one particular downstream location). Due to the very large storage requirements involved with the simultaneous data acquisition of 500 sampling locations, it was not possible to permit the usual 6 bit digital intensity values, i.e. 64 grey levels. Instead, array size limitations dictated that only 5 bits per pixel or 32 grey levels could be utilised. This array limitation was a function of the host computer used (Micro PDP11/73 with 16-bit direct addressing) and could easily be overcome through the use of an alternative computer facility with sufficient directly addressable memory (32-bit or more). Typical sampling populations involved 10,000 sequential field acquisitions, requiring 200 seconds per location and providing 5 million individual data samples for each analysis. Comparative analyses using a 6-bit image with fewer sampling locations per line yielded no significant differences in results, allowing the 5-bit analysis technique to be used with a degree of confidence.
The digital imaging fluctuating flow quantity analysis procedure may be demonstrated by the following graphical representation.

(c) **Flow Measurement Details**

The mean longitudinal turbulence intensity profiles obtained from hot-wire measurements over the range 2.0 to 12.0 X/D, at 2.0 D intervals (first reported in Figures 18a to f) have been replotted together with both the turbulent zonal turbulence intensities and comparative r.m.s. pixel intensities over the same range (Figures 58a to f), at the test Reynolds number. The results for both the hot-wire distributions and r.m.s. pixel fluctuations have been normalised by their centreline intensity values.
5.4 Summary

This chapter has outlined the investigative measurements undertaken in the study of the two-dimensional flat plate model using pressure measurements, hot-wire anemometry and the digital imaging technique. The initial measurements consisted solely of preliminary model characteristic quantifications and comparative investigations to establish whether the smoke introduction system affected the isolated model's wake. The majority of the detailed measurements were more in-depth comparisons between statistical wake functions obtained using both hot-wire anemometry and the digital imaging technique. In particular, the measurements detailed were intermittency functions, autocorrelation functions and spectral analyses, spatial correlations, wake interface data and fluctuating quantity information.

The following chapter discusses the results of the investigative measurements with respect to both the above-mentioned preliminary data and detailed comparative work. Having completed these discussions, the chapter also investigates the possibility of expanding the imaging system to incorporate complete, two-dimensional flowfield analyses.
CHAPTER SIX

DISCUSSION OF RESULTS

6.1 Introduction

This chapter discusses the results obtained from the comparative hot-wire and digital imaging wind tunnel investigations of the turbulent wake region behind a two-dimensional, thin, sharp-edged flat plate model placed in a uniform crossflow. The discussion of the experimental measurements are presented in the following sections:

6.2 Preliminary Measurements
6.3 Comparative Wake Measurements
6.4 System Expansion into Two-Dimensions

The results of preliminary investigations on the model are discussed in section 6.2, the different measurements being examined in a similar order to those of the previous chapter. The preliminary measurements discussed include surface pressure measurements, spatial correlations (spanwise), mean longitudinal velocities, turbulence intensity profiles and the results of the vortex formation region examination.

The results obtained from the comparative investigations are examined in section 6.3, these being presented in a similar order to that of the previous chapter. The detailed contents of the comparative sections discuss the diagnostic characteristics of the digital imaging technique with respect to the flat plate wake flow through direct comparisons with experimentally acquired hot-wire anemometer data. Where possible, the results obtained for the present study are compared with similar results of previous investigators to further substantiate the experimental findings. In particular, there are instances when the accuracy of the hot-wire results may be questionable, such as within the recirculatory region of the near-wake, and in
such cases, the results of previous investigations using the directionally sensitive pulsed-wire anemometer have also been included.

Section 6.4 considers the possibility of expanding the present one-dimensional system into two dimensions by incorporating laser sheet flow illumination. In particular, the comparative result discussions of section 6.3 are considered with respect to their implications towards the achievement of a two-dimensional statistical image analysis technique.

In accordance with the descriptive title first defined in chapter 5 of this thesis, the frequently referred to 'test Reynolds number' is also used throughout this chapter, where:

\[ 'Test \ Reynolds \ Number' = 1.36 \times 10^4 \]

6.2 Preliminary Measurements

The following preliminary investigations were conducted on the flat plate model and its turbulent wake to determine both the basic model flow characteristics and the possible flow disturbance effects caused by the digital imaging visualization procedure. The following sections examine the surface pressure measurements, spanwise spatial correlation, vortex formation region characteristics and finally, mean longitudinal velocities and turbulence intensities.

6.2.1 Surface Pressure Measurements

The surface pressure measurements, Figure 13, and spanwise base pressure distribution, Figure 14, illustrate typical pressure distributions associated with a thin, flat plate model, both functions being symmetrical and indicating no unexpected model or flow complications. Assuming a constant base pressure over the mid-span, the measured surface
pressure distribution indicated a drag coefficient, $C_D$, of 1.99, as would be expected for this type of model. The spanwise base pressure distribution shown in Figure 14 illustrates a lack of two-dimensionality within the flat plate wake. An attempt to improve this could have been made by incorporating end-plates to limit the influence of the wall boundary layer/model interaction. Unfortunately, the nature of the digital imaging technique dictated that end-plates could not be used as their presence would have obscured the view of the near-wake region. Further quantification of the wake two-dimensionality is undertaken in the following sub-section, which examines the spanwise spatial velocity correlation function.

6.2.2 Spanwise Spatial Correlation Measurements

The hot-wire spanwise correlation function, Figure 15, further substantiates the spanwise base pressure distribution indication that the wake flow was only 'weakly' two-dimensional, the calculated integral length scale, $L_{uz}$, being 1.57 D. The accuracy of any hot-wire measurements within the recirculating near-wake region must, however, be questioned, and it would seem probable that this integral length scale and the correlation function itself, have both been overestimated due to the directional insensitivity of the sensor probe.

6.2.3 Vortex Formation Region Characteristics

The longitudinal static pressure distribution shown in Figure 16 illustrates a typical near-wake behaviour, with the minimum static pressure location, presumed to be indicative of the position of vortex formation, being at 1.125 D. The characteristic wake dimension, $d'$, taken as the distance between the turbulence intensity peaks in the transverse wake distribution (at the aforementioned minimum static pressure location), Figure 17a, was measured as 82.5mm (equivalent to 1.624 D).
Using the base pressure coefficient measured in section 6.2.1, the base pressure parameter, \( k \), may be calculated to be,

\[
k^2 = 1 - C_{pb} = 1 - (-1.14), \ \text{i.e.} \ k = 1.463.
\]

Using the relationship, \( U_b = k U \), gives \( U_b = 5.852 \).

The Universal Strouhal number, \( S_{t*} \), may then be found from,

\[
S_{t*} = f_t \times \frac{d}{U_b},
\]

where \( f_t \), the vortex shedding frequency at the test Reynolds number is 12.15 Hz (reported later in this chapter, section 6.3.2).

Hence,

\[
S_{t*} = 12.13 \times 0.0825 / 5.852 = 0.171
\]

The Universal Reynolds number, \( R_{e*} \), may also be calculated from,

\[
R_{e*} = U_b \times \frac{d'}{V} = 3.24 \times 10^4
\]

The above-calculated Universal Strouhal number, \( S_{t*} \), of 0.171 was uncorrected for model blockage and using the corrected Strouhal number for the flat plate, 0.142 (section 6.3.2), a corrected Universal Strouhal number, \( S_{t*} \), may be re-calculated from,

\[
S_{t*} = \frac{S_{t*}}{k} \times \frac{d'}{D_N} = 0.158.
\]

The Universal Strouhal number of 0.158 is in excellent agreement with the previous reported values of Simmons (1977) and Griffin (1978), as previously discussed in section 2.3.
6.2.4 Mean Longitudinal Velocities and Turbulence Intensity

The principal objective of the mean velocity wake traverses (Figures 18a to f) was to examine the wake characteristics associated with the three independent model configurations listed below:

(i) the isolated flat plate,

(ii) the plate with smoke-tube, and

(iii) the plate, smoke-tube with base-bleed.

Figures 18c to f, comparing the above-listed mean velocity and turbulence intensity distributions at downstream locations of between 6.0 and 12.0 X/D, respectively, illustrate that, within the bounds of experimental inaccuracy, there was no quantifiable wake influence due to the smoke-injection technique. This was not unexpected for this particular model as the relatively small dimensions of the smoke-tube (10.0mm diameter compared to 50.8mm plate width), combined with the very low base-bleed rates required for visualization, were physically insignificant to the turbulent wake structure. Further measurements of the shedding frequency (section 6.3.2), at the test Reynolds number, were also found to be constant for the three cases cited above, with only slight (0.1 Hz) variations in frequency being observed over a wide excessive base-bleed range. Whilst the visualization technique was found not to unduly influence the model wake characteristics in this particular model configuration, it would seem appropriate to briefly examine the influence of smoke seeding on all future model geometries considered for study using the digital imaging technique. However much the imaging technique may prove to be an invaluable experimental tool for this particular model, it would prove to be worthless if the fundamental flow characteristics of other model geometries were influenced in order to undertake such studies.
The wake centreline mean velocity and turbulence intensity profiles (Figures 19a and b) have been compared with previous results obtained by Bradbury (1976), for a similar model geometry using both hot-wire and pulsed-wire anemometers. Although Bradbury's data is limited in downstream extent, the inaccuracies involved with a directionally insensitive instrument, such as the hot-wire anemometer, are very evident. Further comparative studies conducted by Bradbury highlighted the near-wake region inaccuracies (locations < 4.0 X/D) inherent in hot-wire anemometer studies, the pulsed-wire comparison results achieved at downstream locations greater than 4.0 X/D yielding far better correlations between the hot-wire and pulsed-wire anemometers.

Having established the basic flow characteristics of the flat plate model, the following section examines in detail the comparative hot-wire and digital imaging results obtained for the model wake.

6.3 Comparative Wake Measurements

The following section discusses the results obtained from comparative studies of the two-dimensional, thin, flat plate model. Comparisons have been drawn from hot-wire anemometry data and the results of the digital imaging technique, the individual sub-sections being as follows:

6.3.1 Intermittency
6.3.2 Autocorrelation and Spectral Analysis
6.3.3 Spatial Correlation
6.3.4 Interface Statistics
6.3.5 Mean Fluctuating Turbulence Quantities

Precise details of data acquisition procedures and technical definitions related to these discussions may be found in Chapters 4 and 5 of this dissertation.
6.3.1 Intermittency

The hot-wire and pixel intermittency functions obtained with the model normal to the flow direction at locations of between 2.0 and 12.0 X/D, at 2.0 D intervals are shown in Figures 23a to f. Additional comparative results obtained at alternative Reynolds numbers of 2.05 and 2.73 * 10^4, corresponding to 6.0 and 8.0 m/s at a downstream location of 6.0 X/D are shown in Figures 24 and 25, respectively. It should be noted that the pixel intermittency function was formed through the observation of 512 individual pixel locations across the wake width, whilst the hot-wire intermittency function was determined by individually acquired intermittency factors obtained with a probe sequentially located at 0.25 D intervals.

Figures 23a and b, corresponding to downstream locations of 2.0 and 4.0 X/D, respectively, appear to indicate that within this region the digital imaging technique underestimated the intermittency function in comparison to the hot-wire system. Further downstream, from 6.0 to 12.0 X/D, Figures 23c to f indicate an excellent agreement between the two techniques. Figures 24 and 25 also show excellent agreement for the alternative Reynolds numbers at the downstream location of 6.0 X/D. Primarily, the overall excellent agreement between the two intermittency functions produced by the independent techniques would appear to reinforce the details of their individual operating procedures and validate their use in intermittent turbulent flow regimes. As indicated in section 5.3.1, however, hot-wire intermittency detection normally requires the establishment of somewhat arbitrary threshold limits, whereas the digital imaging technique turbulence discriminator is assumed to be an exact 'on' or 'off' indicator. To account for the limited but observable discrepancies between the results of the two techniques, it is necessary to consider their more intimate operational details.
An introduction into the use of hot-wire sensors as turbulence detecting devices has been reviewed in sections 2.3 and 5.3.1. The concepts of 'memory time' and 'variable threshold levels' has led to many uncertainties in the past with regard to the establishment of accurate intermittency functions, and although more time consuming due to its computational nature, the digital hot-wire intermittency system would, from certain aspects, appear less arbitrary. The choice of turbulence threshold limit, for instance, was determined through experimentation, whereas the majority of analogue detection systems require continuous threshold limit adjustment (dependent on the flow conditions at the probe location). Figure 20 indicates how the digital threshold level was extrapolated from the various intermittency factors obtained at different freestream velocities. The exact choice of threshold level was, however, complicated by the noise component of the velocity signal which became more prominent at lower freestream velocities. Whilst the use of passive low-pass filtering may have reduced the sensor noise component of this system, it was evident that ground line 'spikes', caused by the host computer, were also a significant contributory source. Any error in the establishment of this threshold limit would cause small but possibly significant intermittency factor inaccuracies which, due to their nature, would lead to a persistent under- or over-estimation of the entire intermittency function.

In addition to the above-mentioned discriminator characteristics, hot-wire signals may also be complicated by wake-induced fluctuations. As previously discussed in section 2.3, irrotational flow velocity fluctuations may either be a direct cause of the wake motion or be a consequence of the entrainment mechanism. The former indicates that possible intermittency factor overestimates may occur through wake-induced irrotational fluctuations being indistinguishable from those of turbulent flow. The latter aspect of entrainment indicates that through the actions of vortex stretching and engulfment, irrotational
fluid may be converted to turbulent fluid. The shearing and viscous forces involved may cause irrotational flow velocity signals to exceed the turbulent state threshold before that flow may truly be considered to be turbulent. The exact extent to which such inaccuracies occur has not been established and remains open to widespread conjecture, although it would seem reasonable to assume that intermittency overestimates due to the above fluctuations will be greatest in the near-wake region where the greatest entrainment and most vigorous wake motions occur. This turbulence discriminator is discussed in more detail in section 6.3.4 which examines the interface crossing frequency distribution achieved during these intermittency function analyses.

The uncomplicated digital imaging discriminator required no threshold level (black background) and the memory time of the detector was determined by the integration period of the imaging device. Theoretically, such a detection system would be ideal, in practice, however, there are certain experimental complications. In particular, errors will occur if insufficient light is scattered from the smoke particles to be detectable, or if the sensor used is incapable of detecting low light intensities. Although similar, these system properties are mutually exclusive, and to illustrate this, consider an experiment where the illuminating transverse laser beam is slowly traversed downstream from the near-wake region as shown below.
Initially, within the vortex formation region, the injected smoke is very concentrated and correspondingly, the scattered light very intense. If the light intensity exceeds the maximum resolvable level of the image sensor, the camera lens aperture must be partially closed to restrict the intensity to within sensor limits. The lens aperture closure, however, reduces the lower light intensities so that low smoke concentrations become undetectable. Further downstream at 12.0 X/D, the smoke concentrations and scattered light intensities are much very weaker. Even with the lens aperture wide open and the sensor signal intensified using the camera's +12dB built-in gain facility, the sensor sensitivity is too poor to detect extremely low smoke concentrations. As outlined in section 4.6.5, use of the gain facility decreases the sensor signal-to-noise ratio and increases the degree of dark current or black level fluctuations, dictating that the video signal should only be digitised to five or six bit levels at the most. The choice of digitisation level not only determines the noise component of the intermittency function but also affects its lowest light intensity detection capabilities.

In addition to sensor sensitivity considerations, the more general characteristics of the smoke contaminant may also be considered to affect the ultimate applicability of the imaging technique. The most obvious limitation in this context is that a turbulent, smoke-contaminated flow region may effectively, at some stage in the flow history, become irrotational, smoke-contaminated flow. Whilst smoke 'ghosting' was not a problem in the present study, such an effect may cause serious misinterpretation of flow visualization images under less favourable conditions. A contaminant characteristic that is, however, of relevance to this study is the inability of smoke particles to penetrate the 'viscous superlayer', the region at the instantaneous edge of a turbulent region in which vorticity is transferred to irrotational fluid by the action of viscosity. Smoke is unable to penetrate the viscous superlayer because the ratio of the fluid viscosity to the diffusivity of the smoke - the
Schmidt number - is extremely high (approximately 40,000). The very existence of this characteristic indicates that smoke-visualized wake images are useful in fluid mechanics research, enabling assumptions regarding the existence of smoke and turbulent flow to be made. However, this inability also determines that the smoke/no-smoke interface is not physically equivalent to the turbulent/non-turbulent interface, the two boundaries being separated by the variable superlayer extent. As previously mentioned in section 2.2, Falco (1980) was unable to detect any difference between the smoke/no-smoke and the turbulent/non-turbulent interfaces, and Fiedler and Head (1966) placed more confidence in their 'smoke intermittency detector' than their hot-wire intermittency detector circuit.

Having established the various system characteristics, their possible implications on the comparative intermittency results will now be discussed. At downstream locations of 2.0 and 4.0 X/D the scattered light intensities exceeded the image sensor limit and the lens aperture was partially closed. Figures 23a and b confirm the aforementioned effect of this procedure and show that, at these locations, the imaging technique underestimated the intermittency function. At a location of 6.0 X/D, the lens aperture was wide open, no signal amplification was necessary and Figure 23c shows an excellent agreement between the hot-wire and digital imaging system intermittencies. At 8.0, 10.0 and 12.0 X/D the scattered light became progressively weaker and the +12dB gain facility with varying lens aperture settings was utilised. The use of the gain facility decreased the signal-to-noise ratio of the sensor and increased the number of 'false pixel illuminations' due to 'dark current noise'. Consequently, when examining the 8.0, 10.0 and 12.0 X/D location intermittency functions (Figures 23d, e and f, respectively) it may be reasonable to assume that the pixel intermittency functions may, on occasion, overestimate the true function due to sensor noise, and where the smoke is very weak, also underestimate the function due to the lower limit of the sensor's sensitivity. It is difficult, however,
to detect any consistent errors at these locations, particularly as the hot-wire intermittency function does not decay to zero within the freestream due to its own system noise component. The two higher Reynolds number cases shown in Figures 24 and 25 (at 6.0 X/D), show almost absolute agreement between their hot-wire and pixel intermittency functions.

The comparative intermittency functions appear to indicate that, apart from within the near-wake region of the flat plate model, it is possible to extract very accurate intermittency data from smoke-visualized wakes. It would also appear that the pixel intermittency functions within the near-wake region were underestimated due to the limited sensitivity range of the image sensor, the scattered-light intensity range being too excessive for the sensor to quantify without artificial intensity reduction via lens aperture closure. In order to overcome this problem the Author would suggest that rather than an image sensor with linear sensitivity to light intensity, a better suited sensor for this particular imaging application would have an exponential sensitivity as indicated below whilst, of course, exhibiting a highly stable 'dark current'.

![Idealised Sensor Response](Image)

**Idealised Sensor Response**
The proposed image sensor would be highly sensitive to low light intensities but relatively insensitive to high intensities, enabling accurate pixel intermittency function analyses at all light intensities. Unfortunately, such a device is not commercially available and would appear to have limited application to other imaging problems.

The interface location error caused by the smoke being unable to penetrate the viscous superlayer would appear not to be a significant problem in this application, and within the experimental accuracy of the present study the smoke/no-smoke boundary may be considered coincidental with the turbulent/non-turbulent interface.

The major advantage of the digital imaging approach to intermittency would appear to be the aspects of experimental expedience and variable spatial accuracy. Before expanding these features it may be prudent to mention that the accuracy of any 'ideal' intermittency probe is proportional to the number of intermittent events encountered during the sampling period, rather than the overall sampling duration or sampling rate. For instance, taking the case of vortex shedding from a bluff body, the intermittent events are predominantly the Strouhal vortices. If a probe samples for 5 seconds and the vortices are shed at, say, 5 Hz, only 25 events are encountered, whilst if the shedding frequency is 10 kHz, 50,000 events are witnessed during the same period. The relative accuracy, therefore, of the intermittency function will depend largely on the number of detected events as well as on the other physical system characteristics such as those previously mentioned with respect to signal noise, sampling rate, turbulence discriminator function, etc.

Appreciating the above-mentioned accuracy considerations dictates that in order to achieve an equal number of intermittent events, the hot-wire and digital imaging techniques should sample for the same duration regardless of their different sampling rates (5 kHz and 50 Hz,
respectively). The major advantage of the imaging technique is that it simultaneously samples 512 locations (1 line of the video image) compared to the single location sampled by the hot-wire probe. In other words, the present pixel intermittency detection system offers a 512-fold improvement in experimental expedience. In practice, the spatial accuracy of the imaging technique is also far greater than the traversing grid normally adopted with an anemometer probe. The results reported in Figures 23a to f, for instance, represented approximately a sample per 1.0mm in the case of the imaging technique, whilst the hot-wire traverse sampled at every 12.7mm, although this could obviously be refined if desired. In the hot-wire case, however, finer sampling would incur excessive experimental time demands. These considerations theoretically equate 100 seconds of imaging data to an equivalent hot-wire traverse of 67 minutes. In addition, the spatial accuracy of the digital imaging technique may also be simply varied through the use of camera lenses of different focal lengths, offering the possibility of extremely high spatial accuracy (assuming a more precise illumination beam could also be provided), if desired.

The individual imaging intermittency functions, Figures 23a to f, have been used to plot the mean iso-intermittency contour map of the flat plate wake from 2.0 to 12.0 X/D, at the test Reynolds number, Figure 26. The iso-intermittency contour map allows an immediate global representation of intermittency factors, highlights regions of interest where the spatial extent of intermittency may be similar, and allows intermittency factor gradients to be assessed in directions other than those in which the measurements were acquired. The contours indicated in Figure 26 have been interpolated by hand, with the chosen contours being measured directly from the individual intermittency functions. With 500 data points available per function, and with a number of such functions being obtainable within a relatively short experimental duration (100 seconds), it may be observed that such iso-intermittency contour plots
should, perhaps, be better constructed using quadratic interpolation (or similar) computational techniques. In the event of a large number of these contour plots being required, the adoption of a computational contour plotting routine would be highly recommended.

Although not directly related to the comparative studies being discussed in this section, it would seem appropriate to briefly examine the hot-wire intermittency detector, as applied to the measurement of 'turbulent' and 'non-turbulent' (or zonal) velocity and turbulence intensities. Returning to the results of the preliminary hot-wire traverses, Figures 21a and b show the measured turbulent, non-turbulent and standard 'combined' zone mean velocity and turbulence intensity distributions for a downstream location of 12.0 X/D, at the test Reynolds number (further examples of turbulent zone distributions are included in section 6.3.5). According to Phillips' (1955) theory, the r.m.s. longitudinal fluctuation intensities within the irrotational flow zone decrease as the square of the distance from the wake centre-plane. Thomas (1973) found agreement with Phillips' theory in his investigation using conditional sampling of a plane turbulent wake, but only up to the half-intermittency (Y = 0.50) point. In order to examine this relationship, the square-root of the non-turbulent turbulence intensities have been plotted against transverse distance for downstream locations between 2.0 and 12.0 X/D, at 2.0 D intervals, again at the test Reynolds number (Figures 22a to f). Whilst Figures 22a and b, corresponding to locations 2.0 and 4.0 X/D, respectively, appear to offer little evidence of a simple relationship between the square-root of non-turbulent turbulence with transverse distance, whilst Figures 22c to f, corresponding to locations 6.0, 8.0, 10.0 and 12.0 X/D, would appear to support such a theory. Indeed, the linear relationship exhibited over these locations would appear to extend almost to the wake centreline, far beyond the half-intermittency limit reported by Thomas. It would seem prudent, however, to regard these results with a degree of caution as later discussions
(section 6.3.4) will reveal doubt regarding the turbulence discriminator used for this study, although it may be assumed that the zonal data does relate directly to non-turbulent flow not in the process of being entrained (i.e. displaying velocity fluctuations of 0.2 percent or less).

It is not possible to interpret the results obtained in this respect within the near-wake region (locations < 4.0 X/D) as the previously mentioned turbulence discriminator errors associated with this region indicate that the zone averages measured were obviously in error. The remaining data would, however, appear to confirm Phillips' (1955) theory with regard to the transverse decay rate of non-turbulent zone velocity fluctuations.

6.3.2 Autocorrelation and Spectral Analysis

Time-dependent flow characteristics were examined using both the digital imaging technique and a single hot-wire anemometry sensor located wholly within the irrotational flow region. Figures 27a to d show the autocorrelation functions and spectral analyses achieved with the imaging technique over the Reynolds number range of 6.82 * 10^3 to 2.73 * 10^4, corresponding to a freestream velocity range of 2.0 to 8.0 m/s, at 1.0 m/s intervals. Figures 28a to d show the equivalent autocorrelation functions and spectral analyses obtained using the hot-wire anemometer (situated outside the wake region at 2.0 Y/D), the functions and analyses being achieved at two separate sampling frequencies (244.2 Hz and 61.0 Hz). The results of the individual tests at any one particular Reynolds number are not identical in shedding frequency because they were obtained from different experiments. Depending on the Reynolds number, a freestream velocity error of ±1.0 percent between similar tests may, for instance, give rise to shedding frequency variations of ±0.3 Hz. Shedding frequency analyses from identical experiments are, however, reported later in this section where simultaneous analyses at limited Reynolds numbers prove that both methods detected identical frequencies.
Figures 27a to d clearly show that the digital imaging technique is capable of extracting vortex shedding frequencies from the real-time sequential edge detection analysis of a smoke-visualized wake. As demonstrated by the increasing rate of decay of the autocorrelation functions and shedding frequency spectral intensities with increasing Reynolds number, the technique is, however, severely limited by the relatively low sampling frequency of 50 Hz. A similar decay rate may be observed for the 61.0 Hz hot-wire autocorrelation functions in Figures 28a to d, the 244.2 Hz sampled functions being significantly improved. Whilst the low sampling rate of the imaging technique is an obviously undesirable characteristic of a practical frequency detection system, the fundamental operational implications of these results would appear very encouraging, allowing sampling frequencies to be improved in future system developments.

The digital imaging technique is able to provide spatial information regarding the turbulent wake interface motion from which the shedding frequency may be established. The technique provides, therefore, Lagrangian statistics rather than the traditional Eulerian statistics normally achieved using a single-location probe such as the hot-wire anemometer. Placing a hot-wire probe outside a turbulent flow relies on the turbulent flow structures to induce velocity fluctuations in the irrotational flow, the frequency of these induced fluctuations being equivalent to that of the flow structures. The digital imaging edge detection technique, on the other hand, traces the physical motion of the turbulent 'outer interface' (as denoted by the smoke/no-smoke boundary) and analyses the frequency of the turbulent motions directly through their interface fluctuations.

An interesting feature of both the digital imaging and hot-wire autocorrelation functions shown in Figures 27a to d and 28a to d, respectively, is the low frequency component waveforms superimposed on the expected autocorrelation
functions. Careful examination of these functions indicates that at the test Reynolds number (Figure 27b) this secondary underlying frequency was composed of four approximately 0.5 Hz components, each having a phase-shift of 90 degrees. At a Reynolds number of $2.39 \times 10^4$ the frequency component was approximately 1.1 Hz and 1.7 Hz at a Reynolds number of $2.73 \times 10^4$ (Figure 27d). The origin of these low frequency components is not immediately obvious but it would seem likely from the above results that they are due either to tunnel freestream velocity fluctuations or a frequency 'beating' effect caused by the 'phase-jitter' of the vortex shedding (which itself could be influenced by tunnel velocity fluctuations). This postulation would appear to be reinforced by the audible 'hum' and physical low frequency vibration (only evident by careful examination) of the tunnel working section when operating at freestream velocities greater than 4.0 m/s. Whilst the operational nature of a wind tunnel thyristor speed control unit may account for small velocity fluctuations of this nature in a standard open-return tunnel, it would appear reasonable to assume that the static pressure rise in the smoke tunnel (caused by the smoke filtration units) may aggravate the problem of maintaining a perfectly constant tunnel speed. The subject of these low frequency components will be returned to later in this sub-section when experiments with the flat plate model at angles of incidence to the freestream are discussed.

Figures 29 and 30 show the comparisons between the hot-wire and digital imaging shedding frequencies and Strouhal numbers for the flat plate model normal to the freestream at Reynolds numbers between $6.82 \times 10^3$ and $2.73 \times 10^4$, corresponding to 2.0 to 8.0 m/s, at 1.0 m/s intervals. The vortex shedding frequency relationship with Reynolds number is linear over the experimental Reynolds number range and, from Figure 29, the Strouhal number may be calculated to be 0.154. This calculated value is represented on Figure 30, which shows the individual Strouhal numbers for the shedding frequencies detected at each Reynolds number.
Correcting the Strouhal number for blockage effects, following recommendations of the E.S.D.U. Code 80024 (1980), gives $St_c$ to be equal to 0.142.

The Strouhal numbers obtained are in agreement with those of previous investigators (see section 2.3 for experimental details), uncorrected Strouhal numbers being reported as:

<table>
<thead>
<tr>
<th>Source</th>
<th>Strouhal Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fage and Johansen (1927a)</td>
<td>0.146</td>
</tr>
<tr>
<td>Kiya and Matsumura (1985)</td>
<td>0.146</td>
</tr>
<tr>
<td>Donoso et al (1983)</td>
<td>0.153</td>
</tr>
</tbody>
</table>

A blockage corrected Strouhal number of 0.142 was reported by Davies (1975), which is also in reasonable agreement with Fackrell's (1975) theoretically predicted zero blockage Strouhal number (0.146).

In addition to the detection of vortex shedding frequencies via wake interface motions, the digital imaging technique was also able to detect temporal frequencies through the observation of fluctuating image intensities within the fully turbulent wake structure. Comparative hot-wire measurements were undertaken by placing the hot-wire sensor within the hot-wire wake, rather than outside it as previously detailed. Figure 31 shows the spectral intensity distribution of the principal shedding frequencies detected in the normal plate wake at downstream locations of 2.0, 4.0, 8.0 and 12.0 X/D using the pixel intensity autocorrelation analysis procedure. Figure 32 shows the equivalent spectral intensity distribution at the 6.0 X/D downstream location obtained by the unfiltered hot-wire anemometer system.

Figures 31 and 32 indicate that the dominant vortex shedding frequency is detectable within the turbulent wake, the wake centreline region possessing a frequency component double that of the vortex shedding frequency. When comparing the distributions achieved by the digital imaging and hot-wire
methods it is necessary to appreciate exactly what the two techniques are correlating. The digital imaging pixel intensity autocorrelation analysis, for instance, correlates the temporal fluctuations of a particular pixel's intensities. If the pixel location under consideration is within the turbulent flow it will have an intensity value proportional to the smoke intensity concentration, whilst when within the irrotational flow regime it will have an intensity value of zero. Thus, a pixel location completely within the irrotational flow will have no registered intensity values and will record a zero temporal correlation. Within the wake region, the spectral intensity of the dominant frequency will be proportional to the relative strength and periodicity of the light intensity fluctuations. In contrast, the hot-wire anemometer system correlates fluctuating velocity components at a single location in space with respect to time. If the hot-wire probe is within the turbulent region the velocity signals are complicated by turbulence fluctuations and when outside the wake, within the irrotational flow, a smoothly varying, wake-induced velocity signal is detected. The distribution of the vortex shedding frequency spectral intensity shown in Figure 32 is complicated by the probe sensing the fluctuations in both turbulent and non-turbulent flow regimes. The hot-wire spectral intensity distribution demonstrates that the most strongly correlated velocity signals are to be found outside the wake, where the velocity component fluctuations are sinusoidal in appearance and uncomplicated by wake turbulence. A comparison of the results in Figures 31 and 32 would, however, indicate that the spectral intensity peak at 6.0 X/D within the wake region is located at 1.3 Y/D for both the hot-wire and interpolated digital imaging results. In the absence of more detailed comparisons it would appear that the strongest velocity fluctuations may, perhaps, be correlated with the strongest pixel intensity fluctuations. This finding is discussed further in section 6.3.5 which reports on the comparisons between mean fluctuating velocity and pixel intensities.
The spatial extent of the double vortex frequency component (24.2 Hz) across the half-wake gives an indication of the extent to which the wake vortices may be detected across the wake centreline. Once again, the results from the hot-wire anemometer are complicated by the fact that the probe senses both turbulent and non-turbulent velocity fluctuations, inferring that the absolute extent of the double frequency component is not necessarily correlated with the presence of the turbulent wake structure alone. In contrast, the digital imaging pixel intensity fluctuations correspond solely to turbulent flow detections (non-turbulent flow being smoke-free and appearing black) and a significant double vortex frequency component may only be attributed to the presence of wake structures, indicating the extent to which wake vortices cross the centreline. This finding is discussed further in section 6.3.4 which examines the wake interface statistics in more detail. It should be noted, however, that the double frequency component of 24.2 Hz reported in the above Figures is very close to the digital imaging Nyquist frequency of 25.0 Hz and is, therefore, difficult to accurately identify using this technique.

Figures 33a to g and 34a to g show the autocorrelation functions and spectral analyses achieved with the flat plate model at angles of incidence between 90 and 30 degrees to the freestream, at 10 degree intervals, using the digital imaging edge detection technique and hot-wire anemometry, respectively. The hot-wire results (Figures 34a to g) provide comparisons of the aforementioned functions using two sampling frequencies of 244.2 Hz and 61.0 Hz. Before comparing these results in detail, it should be noted that the physical dimensions of the flat plate model affected its use at low angles of incidence to the freestream. Although the model configuration does not restrict comparisons between the two frequency detection techniques it does limit the model's comparability with results of other investigators who have used isolated models with more acute edge angles to produce results at incidence angles of up to 30 degrees.
The sketches below illustrate that at incidence angles of less than 45 degrees to the freestream the model no longer presented a sharp-edged plate to the flow and at less than 40 degrees the smoke-tube protruded beyond the 'shadow region' of the plate.

90 Degrees 60 Degrees 30 Degrees

Direct comparison of the digital imaging and hot-wire autocorrelation functions and their corresponding spectral analyses illustrate clearly that the digital imaging technique may be successfully used to measure shedding frequencies over a range of flat plate incidences from 90 to 40 degrees (discrepancies between the shedding frequencies measured using the hot-wire and imaging techniques being less than ±0.05 Hz). At a plate incidence of 30 degrees to the freestream, the shedding frequency detected by the hot-wire was inconsistent between tests (5 percent variation) and was greater than the Nyquist frequency of the digital imaging technique. Hoole (1968) also recorded variable shedding frequencies at a plate incidence of 30 degrees to the freestream, these variations reportedly being as great as 25 percent. The results of the shedding frequency analyses are plotted in Figure 35 and show clearly that over the range 90 to 40 degrees of incidence, the Strouhal number of the plate, Figure 36, remains constant when using the normally projected plate dimension (i.e. \( St = \frac{fD\sin\theta}{U_0} \), where \( \theta \) is the angle of incidence of the plate to the freestream).
The low-frequency components mentioned earlier in this subsection may again be observed in the autocorrelation functions of both the digital imaging and hot-wire techniques (Figures 33a to g and 34a to g). The frequency of these underlying components may be seen to vary greatly over the incidence range and as all of these results were achieved at constant tunnel velocity it may be deduced that such low-frequency fluctuations are not solely dependent on the freestream velocity. In particular, Figure 34g shows that at 30 degrees incidence a two-phase component of approximately 1.5 Hz may be observed, Figure 34d shows a four-phase, 0.9 Hz component at an incidence of 60 degrees and Figure 33c shows a similar component at 70 degrees incidence (0.7 Hz). The following table compares these secondary underlying frequency components against the vortex shedding frequency for both the above-mentioned incidence experiments and the previously detailed normal plate experiments.

<table>
<thead>
<tr>
<th>Plate Incidence (Degrees)</th>
<th>Low Freq. (Hz)</th>
<th>Vortex Freq. (Hz)</th>
<th>Reynolds No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>0.5</td>
<td>12.06</td>
<td>1.36 x 10^4</td>
</tr>
<tr>
<td>70</td>
<td>0.7</td>
<td>13.05</td>
<td>1.36 x 10^4</td>
</tr>
<tr>
<td>60</td>
<td>0.9</td>
<td>14.40</td>
<td>1.36 x 10^4</td>
</tr>
<tr>
<td>90</td>
<td>1.1</td>
<td>21.30</td>
<td>2.39 x 10^4</td>
</tr>
<tr>
<td>90</td>
<td>1.7</td>
<td>24.10</td>
<td>2.73 x 10^4</td>
</tr>
<tr>
<td>30</td>
<td>1.5</td>
<td>28.95</td>
<td>1.36 x 10^4</td>
</tr>
</tbody>
</table>

Table 3. Secondary Frequency Components

Although the results listed in Table 3 are not conclusive, it would appear that the low-frequency components present in the autocorrelation functions are dependent on the vortex shedding frequency rather than the flow Reynolds number. These results have been plotted overleaf, but are too limited to provide any conclusive correlation between the low-frequency components and vortex shedding frequencies.
The trend of the results reported would, however, correspond to the concept of 'phase-jitter' of the vortex shedding frequency, causing a 'low-frequency beating'. It would seem plausible that any periodic freestream velocity fluctuations would also contribute to this 'phase-jitter' and that the extent of the tunnel freestream variations may themselves be dependent on the Reynolds number of the flow. The results achieved during the course of this study do not provide conclusive proof of this postulation but are sufficient to indicate that the low-frequency components are independent of sampling technique.

The digital imaging technique using the edge detection system does not afford any time advantage over a single-sensor anemometer system, and at present, is limited in application by its 50 Hz rate. The imaging technique does, however, correlate the motion of the wake interface (as indicated by the smoke/no-smoke boundary), rather than relying on induced potential flow fluctuations as measured by the hot-wire anemometer system. (Further implications of this system characteristic are demonstrated in section 7.3, when secondary shear layer instabilities are reported for the near-wake of a circular cylinder). The pixel intensity autocorrelation system allows 25 separate autocorrelation functions to be simultaneously acquired across the wake, and
offers greater experimental expedience in this respect than a single-sensor anemometer. In addition, the pixel intensity autocorrelation system only correlates turbulent flow temporal characteristics, whereas a standard hot-wire anemometer system correlates both turbulent and non-turbulent flow conditions.

6.3.3 Spatial Correlation

Spatial correlation functions were obtained using both the digital imaging technique and hot-wire anemometry. The complex traversing facilities required to facilitate hot-wire spatial correlations were not available in the smoke tunnel and instead, measurements were undertaken within the boundary layer tunnel (section 4.2). Digital imaging spatial correlations were achieved through longitudinal wake illumination (section 5.3.3). The hot-wire spatial correlation function obtained from measurements in the boundary layer tunnel on a normal, two-dimensional 30.0mm flat plate model at the test Reynolds number, corresponding to a freestream velocity of 6.75 m/s is shown in Figure 37. The correlation function does not have the 'normal' correlation form, the 0.0 X/D displacement correlation coefficient being -0.69, as opposed to a 'standard' value of +1.0. The anti-correlated nature of the function is due to the two hot-wire sensors being located on opposite sides of the wake to avoid probe interference (see section 5.3.3). As indicated in Figure 37, the correlation distance between the anti-correlation peaks is 5.33 D, whilst the distance between the positive correlated peaks is 5.5 D. This difference in correlation lengths is consistent with an increasing relative velocity of the wake vortices with downstream distance, the spacing increasing continuously until the vortices attain the same velocity as the freestream flow (at an infinite downstream distance behind the model). Consequently, a nominal longitudinal vortex spacing ratio (a) of 5.33 D is in good agreement with the findings of Fage and Johansen (1927a) who reported a ratio of 5.25 D and Hoole (1968) who determined the
longitudinal vortex spacing ratio to be 5.30 D. As the digital imaging technique could not be used in the boundary layer tunnel and adequate hot-wire traversing could not be undertaken in the smoke tunnel facility, the establishment of the longitudinal vortex spacing ratio in the boundary layer tunnel may appear somewhat academic. The re-affirmation of the flat plate longitudinal vortex spacing ratio was, however, felt to be a worthwhile exercise, as a good appreciation of the experimental requirements to perform such a correlation procedure was attained. The remaining spatial correlation functions described in this section were all achieved in the smoke tunnel facility using the digital imaging technique.

The digital imaging technique allows a great deal of flexibility in spatial resolution and accuracy through the use of different focal length lenses and focussing distances. Figure 38 shows comparative spatial correlation functions obtained at Reynolds numbers of $6.82 \times 10^3$, 1.36 and $2.73 \times 10^4$, corresponding to freestream velocities of 2.0, 4.0 and 8.0 m/s with the plate normal to the freestream direction. These results were obtained with the 4.8mm 'fish-eye' lens, the camera being positioned outside the tunnel working section window as sketched below:
Figure 39 compares similar functions obtained at Reynolds numbers of $6.82 \times 10^3$ and $2.05 \times 10^4$, corresponding to freestream velocities of 2.0 and 6.0 m/s, these results being obtained using the 8.5 mm 'wide-angle' lens with the camera positioned beneath the working section glass floor as illustrated in the following sketch:

![Sketch of experimental setup](image)

The experiments recorded in Figures 38 and 39 were conducted individually and physically separated by a number of months. Although the agreement between the correlation lengths is good (5.32 D and 5.28 D), the two experiments highlighted the crucial aspect of accurate sensor pixel/spatial calibration. In particular, it is necessary to examine the degree of possible errors caused by a poor calibration using, for instance, the 4.8mm focal length lens. Using a 2/3 inch camera lens mount, the relationship between focal length and object area is defined by the following formulae:

- For a 2/3" Sensor:
  - $W = 8.8 \times \frac{L}{f}$
  - $H = 6.6 \times \frac{L}{f}$

where $f$ is the focal length of the lens in mm, $W$ is the horizontal dimension of the object in mm, $H$ is the vertical dimension of the object in mm, and $L$ is the distance from the lens to the object in mm.
The sketch below illustrates the physical dimensions associated with the imaging arrangement used to produce the spatial correlation in Figure 24.

Considering the horizontal dimension only (direction in which measurements were taken), the above formula shows that at a focusing distance of 250 mm, the object horizontal dimension is 458 mm (4.8 mm focal length lens). If when calibrating the image system the location of the illumination plane was in error by 4.0 percent (+10.0 mm in the focusing distance), the object horizontal dimension would be in error by 18.6 mm. In terms of the present spatial correlation dimensions, this could cause a 5.30 D dimension to be interpreted as anything between 5.08 D and 5.52 D, which would obviously represent a serious error. To maintain good calibration accuracy, it was possible to use the visualization laser beam as an alignment aid, the laser illuminating the face of an appropriate measuring scale. Whilst this method was reasonably simple to perform using a 5 mW He-Ne laser, safety requirements would necessitate more careful consideration when operating with more powerful lasers.

Having established that the calibration of the image field requires to be very precise, it is also necessary to consider the question of image blur.
General blur details have been previously outlined in section 4.6.4, where it was noted that at 4.0 m/s a 500.0mm horizontal format image (at standard video rates) would have a blur ratio (BR) of 16.0%, the image moving 80.0mm within a 20 ms field period, illustrated below:

As illustrated in Figures 38 and 39, the correlation length of the longitudinal vortex spacing ratio remained reasonably constant over the Reynolds number range considered, indicating that varying blur ratios did not adversely affect the spatial correlation functions. This may be explained by considering the physical flow images being correlated. The following sketch shows two examples, using circles to represent vortices, illustrating two different blur ratios.

\[ \text{Blur Ratio Example} \]
These sketches demonstrate how the blur ratio does not affect the correlation distance $R(x)$ being measured, but does affect the shape of the correlation function and, in particular, the initial positive correlation section of the function, the integral of which is related to the integral length scale $L(x)$ (as defined in section 5.3.3), Figure 40. An increasing image blur ratio will cause an increased integral length scale $L(x)$, because the apparent images being correlated become 'wider' due to blur deformation. As an approximate comparison between the hot-wire and digital imaging correlations, Figure 37 indicates that the initial positive correlation region for the hot-wire function extends to $1.33 \, D$, whereas in Figure 38, Reynolds number of $6.82 \times 10^3$, freestream velocity $2.0 \, m/s$, blur ratio 7.6 percent, the imaging technique indicates that this positive correlation region extends to $1.43 \, D$.

The snap-shot facility of the CCD camera allowed the consequences of image blur on the integral length scale $L(x)$ to be examined in a controlled manner. Figure 40 shows three separate spatial correlation functions which were all established at the test Reynolds number, using image integration periods of 20, 16 and $8 \, mS$. The integral length scales calculated from these functions are listed below:

<table>
<thead>
<tr>
<th>$L(x)$</th>
<th>Integration Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.83 , D$</td>
<td>$20 , mS$ (approximate)</td>
</tr>
<tr>
<td>$0.81 , D$</td>
<td>$16 , mS$</td>
</tr>
<tr>
<td>$0.77 , D$</td>
<td>$8 , mS$</td>
</tr>
</tbody>
</table>

The snap-shot CCD camera is capable of integration periods as low as $1 \, mS$, but due to the low light levels available, periods of less than $8 \, mS$ could not be used. The $20 \, mS$ integration period is indicated as 'approximate' because using standard scanning conventions, $1.6 \, mS$ of the $20 \, mS$, or so, should be allowed for blanking periods. Whilst not conclusive, the calculated figures illustrate that correction for integral length scale with respect to image blur may be undertaken using the known image integration
period and the calculated image velocity. The 8 mS integration period, however, yielded an integral length scale equivalent to that obtained using the hot-wire, indicating that image blur effects may also be reduced using appropriate imaging sensors.

Figures 41a to g show both the spatial and 'spatial intermittency' correlation functions obtained at angles of incidence between 90 and 30 degrees to the freestream, with 10 degree intervals. The spatial intermittency functions are representative of the correlation between turbulence regions, the presence of the regions, rather than the light intensities within them, being correlated. Figures 41a to g demonstrate reasonable agreement between the spatial and 'spatial intermittency' correlation functions, although the latter functions are slightly less well defined. Using these results together with the previously outlined auto-correlation results, it is possible to calculate the relative velocity \( v_r \) of the wake vortices,

\[
v_r = \frac{a \cdot f}{U_0},
\]

where \( a \) is the vortex spacing distance in m, \( f \) is the vortex shedding frequency in Hz, and \( U_0 \) is the freestream velocity in m/s.

The following table shows the relative wake vortex velocities achieved using the imaging technique and lists the comparable results of Fage and Johansen (1927a).

<table>
<thead>
<tr>
<th>Incidence (Degrees)</th>
<th>Dn ( \times 10^{-3} )</th>
<th>Vortex Spac. ( a/\text{Dn} )</th>
<th>a (m)</th>
<th>St</th>
<th>Rel Vel ( v_r )</th>
<th>F&amp;J 1927a</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>50.80</td>
<td>0.267</td>
<td>5.25</td>
<td>0.154</td>
<td>0.808</td>
<td>0.766</td>
</tr>
<tr>
<td>80</td>
<td>50.03</td>
<td>0.259</td>
<td>5.18</td>
<td>0.154</td>
<td>0.798</td>
<td>-</td>
</tr>
<tr>
<td>70</td>
<td>47.74</td>
<td>0.248</td>
<td>5.19</td>
<td>0.156</td>
<td>0.810</td>
<td>0.756</td>
</tr>
<tr>
<td>60</td>
<td>44.00</td>
<td>0.231</td>
<td>5.25</td>
<td>0.158</td>
<td>0.830</td>
<td>0.761</td>
</tr>
<tr>
<td>50</td>
<td>38.92</td>
<td>0.203</td>
<td>5.22</td>
<td>0.160</td>
<td>0.835</td>
<td>0.789</td>
</tr>
<tr>
<td>40</td>
<td>32.65</td>
<td>0.176</td>
<td>5.38</td>
<td>0.163</td>
<td>0.877</td>
<td>0.817</td>
</tr>
<tr>
<td>30</td>
<td>25.40</td>
<td>0.124</td>
<td>4.88</td>
<td>0.184</td>
<td>0.898</td>
<td>0.840</td>
</tr>
</tbody>
</table>

Table 4. Relative Vortex Velocities at Incidence Angles
With the plate normal to the flow, the corrected flat plate Strouhal number of 0.142 gives a corrected relative velocity of 0.746, which is in reasonable agreement with the Fage and Johansen (1927a) value of 0.766, and the Hoole (1968) value of 0.77. As previously mentioned in section 6.3.2, the results with the inclined plate are only directly comparable with other investigations up to an incidence of 45 degrees due to the physical dimensions of the flat plate model. The results of the above table would seem to indicate that the spatial correlation lengths and relative velocities obtained by the digital imaging technique over this range are also in agreement with those obtained by previous investigators.

The major advantage of the digital imaging spatial correlation technique, as opposed to the hot-wire anemometer two-probe approach, is that of experimental expedience and spatial accuracy. This advantage may be demonstrated by considering the time required to produce a typical spatial correlation function such as that presented in Figure 37. Sampling with a hot-wire system at 0.125 D intervals in the downstream direction up to a maximum of 8.0 X/D requires a total of 64 sampling locations. Allowing for 100 seconds per sampling location (250,000 velocity quantifications) and 20 seconds (minimum) to relocate the probe in both the X- and Y-axes between locations would necessitate a total time requirement of almost 2 hours. In comparison, the imaging technique provided 500 sampled locations (average spatial accuracy of 0.015 D, although not entirely equi-spaced) simultaneously acquired in 100 seconds. The technique also offers variable resolution through the implementation of different focal length lenses and does not require a complex two-dimensional traversing mechanism. Very careful calibration of the pixel correlation function into physical distance at the flow plane being illuminated is, however, required (although errors due to calibration inaccuracies could be avoided through the testing of mechanical devices at the experimental plane with known temporal and spatial characteristics). Having calibrated the imaging system it is, however, possible to undertake numerous experiments at
that same experimental plane without further calibration in extremely quick succession. Indeed, using the above system time requirements, continuous hot-wire testing for 12 hours could enable the production of six spatial correlation functions, whilst the digital imaging technique would produce 430 functions, with more than an eight-fold increase in sampling locations, within the same experimental period.

Whilst the present system is restricted to the analysis of one line of illuminated wake, it would seem reasonable to assume that a two-dimensional illumination plane would offer an experimenter the opportunity of exploring complete flowfields with respect to spatial correlation coefficients within reasonable time constraints. Further discussion on the factors relevant to expanding this particular imaging technique into two dimensions is undertaken in section 6.4.

6.3.4 Interface Statistics

The definitions of the various interface descriptions referenced in this sub-section are given in section 5.3.4. In brief, the interface statistics presented include 'outer interface' (first encountered wake interface as seen from the irrotational flow), 'inner interface' (interfaces encountered within the confines of the 'outer interface' locations at any one particular downstream location) and 'ensemble interface' which refers to the combination of both 'outer' and 'inner interfaces'. Comparative digital imaging 'outer interface', 'ensemble interface' and hot-wire crossing frequency distributions at 6.0 X/D are shown in Figures 42 and 43, for both the test and additional Reynolds number of 2.73 * 10^4, corresponding to a freestream velocity of 8.0 m/s. It may be observed that the hot-wire crossing frequency distributions are complicated in both Figures by false edge detections as indicated by the non-zero value of the distribution functions at transverse locations greater than 3.5 Y/D (the approximate turbulent wake limit in both Reynolds number cases). These false detections were caused by signal noise which has been previously discussed with
respect to the intermittency factor findings of section 6.3.1. As was the case in the intermittency detection, the improved signal-to-noise ratio of the hot-wire system at the Reynolds number of $2.73 \times 10^4$ is evident in the reduced number of extraneous crossing frequencies detected outside the wake region in Figure 43, compared to the results of the lower Reynolds number in Figure 42. In contrast to the hot-wire results, the digital imaging crossing frequency results show no extraneous edge detections outside the expected wake limit, which is again in agreement with the intermittency results of section 6.3.1. Having established that the hot-wire results are prone to an element of signal noise, a closer examination of these Figures may be undertaken.

The intrinsic capability of the digital imaging technique to identify 'multiple interface' crossing locations has provided very interesting results in Figures 42 and 43. In Figure 42, for instance, it may be observed that the digital imaging 'ensemble interface' and hot-wire crossing frequency distributions, whilst not being identical, display good overall agreement with respect to both general characteristics and peak function location. The 'outer interface' distribution, on the other hand, displays a more familiar 'Gaussian-like' distribution with the function peak location being shifted laterally by approximately 0.5 D (away from the centreline).

As mentioned in section 5.3.4, if both the digital imaging and hot-wire systems were capable of detecting all of the turbulent wake interfaces, then the 'ensemble interface' and the hot-wire crossing frequency distributions should be identical. Considering the hot-wire signal noise contribution, it would seem reasonable to conclude that in Figure 42, this was very nearly the case. Examination of the 'ensemble interface' and hot-wire crossing frequency distributions in Figure 43, however, appears to indicate that at the higher Reynolds number, this was no longer the case. Indeed, the hot-wire distribution bears remarkable
similarity with both the overall shape and peak location details of the digital imaging 'outer interface' distribution, and very little similarity to the 'ensemble interface'.

Comparing the individual system distributions in Figures 42 and 43 against each other, it would appear that for the two Reynolds number cases considered, the digital imaging results are reasonably similar, whilst the hot-wire results are not. This would appear to indicate that a fundamental change has occurred with respect to the measured values represented in these Figures. The following discussion will attempt to validate these findings and offers a possible explanation for these obvious dissimilarities.

The literature surveyed in section 2.2 of this dissertation highlighted previous examples of intermittency detections which have attempted to utilise both smoke flow visualization and hot-wire anemometry turbulence detection techniques. Fiedler and Head (1966) presented a method of intermittency measurement which incorporated a photo-electric probe and smoke visualization. The technique was developed to corroborate the intermittency results of their improved version of a hot-wire detection method, but when compared directly at a single location in the flow, the results suggested that the photo-probe could distinguish narrow regions of smoke-free fluid where the hot-wire recorded velocity fluctuations indistinguishable from turbulence. In a later investigation Falco (1980) also combined smoke flow visualization and hot-wire anemometry. Simultaneous recordings of both visual data and hot-wire outputs enabled a study of the turbulent/non-turbulent interface using both smoke and hot-wire observations. Falco verified that the smoke/no-smoke boundary was highly correlated with the turbulent/non-turbulent interface but was unable to provide more conclusive results due to the uncertainties involved in turbulence detection using hot-wire velocity signals. The existence of narrow fissures in the boundary layer flow studied by Fiedler and Head was
confirmed by Murlis et al (1982), indicating that the intermittency circuit employed by the former investigators was incapable of detecting narrow intrusions of irrotational fluid within the turbulent region. In addition to these above-outlined investigations, section 2.3 also reported that Hedley and Keffer (1974) discussed many of the complications of turbulent/non-turbulent decisions in an intermittent flow, and to assist in the comprehension of the present study results it is, perhaps, these complications that must be more fully appreciated.

With respect to the above-outlined difficulties in turbulent/non-turbulent decisions and with particular reference to the experimentally determined crossing frequency distributions (Figures 42 and 43), observed discrepancies between the hot-wire and digital imaging system results may be assumed to be due to either:

(a) 'Smoke gaps' where there is fully turbulent flow, or

(b) An inability of the hot-wire to detect irrotational flow which is strongly influenced by turbulent motions.

In considering the possibility expressed in (a), that the digital imaging system is in error, it should be noted that whilst smoke flow visualization techniques have been universally criticised for retaining smoke patterns ('ghost structures'), turbulent wake fluctuations would appear to offer practically no conceivable possibility for leaving smoke-free zones within a fully turbulent flow regime. However, as previously mentioned on numerous occasions within this chapter, very low concentrations of smoke contaminant could provide too little scattered light to be detected by the imaging sensor, causing 'no-smoke' observations to be registered where there were, in fact, limited smoke traces. It would seem reasonable to assume that at 6.0 X/D where scattered-light levels were satisfactory for the CCD sensor, such low levels of smoke concentration would only occur at a turbulent/non-turbulent boundary, leading to the conclusion that such an error would
affect only the relative location of a detected edge and not the overall distribution of the number of edge detections. 'Smoke-gaps' could also be caused by the 'out-of-plane' passage of high concentrations of smoke contaminant obstructing the image path between the visualized wake and the camera lens. Although this effect may be encountered in densely seeded, three-dimensional flows, the nature of the present study and the excellent agreement between the results obtained for the intermittency functions would seem to indicate that such occurrences were not the cause of 'smoke-gaps'.

The hot-wire turbulence detection defect outlined in (b) would seem to be the primary source of system error in the present study. Certainly, the corroborative evidence previously outlined would appear to reinforce the conclusion that adequate turbulence detection using a single-sensor hot-wire technique is difficult to achieve. In addition to a multitude of different detection circuits currently employed (including the often arbitrary setting of variable threshold levels and memory periods), it would seem apparent that the induced velocity fluctuations within irrotational flow that is in the process of being entrained are, on occasions, practically indistinguishable from those of fully turbulent flow. The evidence obtained from Figure 43 would seem to indicate that at the higher Reynolds number of $2.73 \times 10^4$ the single-sensor digital sampling routine adopted for the present study was to a large extent incapable of detecting more than merely the 'outer' wake interfaces. Although by no means conclusive, the results obtained in Figures 42 and 43 would appear to provide a possible means by which various hot-wire turbulence detection systems could be independently compared against an alternative turbulence detection method.

It is also interesting to note that the differences between the crossing frequency distributions at a Reynolds number of $2.73 \times 10^4$, observed using the digital imaging and hot-wire detection systems (Figure 43), do not noticeably manifest themselves in the corresponding intermittency functions.
shown in Figure 25. The previous discussion concerning the crossing frequency distribution indicates that the hot-wire results should be slightly overestimated over the central (near centreline) region of the function. As the hot-wire results tend to show overall slightly higher intermittency values than the corresponding digital imaging results, it would appear that the very slight differences in the intermittency function due to the aforementioned crossing frequency errors are not immediately discernable.

The hot-wire digital sampling turbulence detection and intermittency technique is not an efficient experimental method and detailed comparative hot-wire measurements of crossing frequency have been restricted to the 6.0 X/D downstream location at the above-mentioned Reynolds numbers. The digital imaging procedure, on the other hand, offers both excellent spatial accuracy (approximately 500 pixels per wake extent depending on the imaging lens arrangement) and simultaneous data acquisition. In view of this, it is a relatively simple undertaking to examine the digital imaging crossing frequencies over a number of different locations, and Figures 44a to e show the 'outer interface' and 'ensemble interface' probability distributions at the test Reynolds number for downstream locations between 2.0 and 10.0 X/D, at 2.0 D intervals. The crossing frequency distributions shown in Figures 44a to e show clearly that the 'outer interface' distributions display a skewed 'Gaussian-type' form, increasing downstream distance reducing the skewness and increasing the functions' resemblance to that of a Gaussian distribution. The 'ensemble interface' distributions also develop considerably in form with downstream distance and it would be conceivable to imagine that at much greater downstream locations (of the order of 100 X/D, for instance), the 'ensemble interface' distribution would closely resemble that of the 'outer interface'. If this were to be the case, hot-wire intermittency and crossing frequency measurements would no longer be significantly different from the digital imaging results. Indeed, a large percentage of past wake
intermittency measurements reported in the literature have been conducted in the far-wake region where the flow has become self-similar and where wake-deficit and turbulence intensity levels were relatively low. In such a situation, it would seem plausible that a hot-wire intermittency detection system (such as that used in the present study) could operate quite satisfactorily and produce accurate crossing frequency distributions.

The simultaneous spatial information offered by the flow visualization technique has been employed to examine the 'multi-valued interface distribution function', i.e. the mean distribution of the number of interface pairs encountered at one particular downstream location. Single hot-wire sensors are not capable of providing such information, and it would not seem feasible to imagine a hot-wire rake with enough integral sensors to approach the spatial accuracy and range required for such measurements. The results are, therefore, unique to a flow visualization technique and cannot be directly compared against known or alternative experimental data. Figure 45a. shows the 'multi-valued interface' distributions for transverse locations located between 2.0 and 10.0 X/D, at 2.0 D intervals. Apart from the near-wake results at 2.0 X/D and 6.0 X/D, the remaining functions would appear to follow a common distribution, the similarity of the functions increasing with downstream distance. A simple explanation as to why the 6.0 X/D results do not appear to follow the trends of the remaining functions is not obvious. It may, however, follow that due to the uncertainty involved in the near-wake results (< 4.0 X/D), interpretation of trends relative to these functions should be avoided. Further investigation of interface multivaluedness should, perhaps, be encouraged in view of these initial findings. The establishment of detailed knowledge concerning the multi-valued nature of the turbulent/non-turbulent interface is of particular importance to the theoretical modelling of intermittent turbulent flows.
Paizis and Schwarz (1974) studied the geometrical properties of the interface in a turbulent wall jet using a multiple array of turbulence detector probes and revealed a highly contorted interface shape. They found that the interface position was multi-valued for as much as forty percent of the time and used the multiple-valued probability density function theory of Lumley (1964, 1970) to predict an interface expected valuedness (average number of interface values) of 2.35. The most significant consequence associated with this multi-valued interface aspect is that it leads to extremely large interfacial surface areas, which is important in the theoretical prediction of entrainment rates. In a recent publication Dancey (1986) developed a simple model for the average local entrainment rate which utilised the aspect of multi-valued interface locations. Dancey, however, also emphasized the need for more experimental information relating to the behaviour of the intermittency (turbulent/non-turbulent) interface. The results of the present study, Figure 45a, indicate that the turbulent/non-turbulent interface was multi-valued for more than seventy percent of the time (locations > 4.0 X/D), which reaffirms the inadequacies of a single-valued interface location postulation. The cumulative multi-valued interface distributions for locations 4.0 and 10.0 X/D have been plotted in Figure 45b, from which the experimental value of the expected valuedness (0.5 probability location) may be observed to be as follows:

<table>
<thead>
<tr>
<th>X/D</th>
<th>Expected Valuedness</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0</td>
<td>1.6</td>
</tr>
<tr>
<td>10.0</td>
<td>1.9</td>
</tr>
</tbody>
</table>

The distributions shown indicate that the expected valuedness may increase further with increasing downstream distance, which would appear to agree in principle with Paizis and Schwarz's (1974) predicted value of 2.35 for a wall jet.
As detailed in section 5.3.4 the digital imaging technique is capable of identifying both 'left' and 'right outer interfaces', allowing independent statistical distributions of these boundaries to be compiled. Once again, a single hot-wire sensor is incapable of simultaneously identifying equivalent boundaries. Figure 46a shows the 'left' and 'right outer interface' distributions for the 6.0 X/D location. The apparent 'spikey' nature of the distribution is principally due to the relatively small sample population of 5,000 interfaces (per 'side'). Figure 46b shows the equivalent 'left' and 'right' distributions after 40,000 samples, these distributions being far less irregular in appearance. The 'outer interface' crossing frequency distribution shown in Figure 44c was re-calculated from the cumulation of the 'left' and 'right' interface distributions shown in Figure 46b, which is presented in its 'raw' detail in Figure 47a. An equivalent cumulated distribution for location 6.0 X/D, Reynolds number of 2.73 * 10^4, freestream velocity 8.0 m/s, is shown in Figure 47b. Whilst an increased sample population would appear to offer greater function continuity, the stationary nature of the wake interface distribution should indicate that the statistical values (mean, variance, etc.) associated with the distributions should be comparatively unaffected by sample size. If, however, low frequency vortex shedding variations occur within the turbulent wake (previously described in section 6.3.2 as frequency beating), function variations could occur and uncertainties with regard to true mean and variance, etc., may consequently have to be expressed.

The interface distributions shown in Figures 46 and 47(a,b) all exhibit an inconsistency at the pixel location corresponding approximately to the +2.0 Y/D location. This 'drop-off' in the expected distribution function was due to the poor response characteristics of the photo-sensitive element corresponding to that particular pixel location on the sensor line used for the acquisition. As explained in section 5.3, it would be normal practice to ignore this line in future experiments as the presence of such 'poor' pixels
may interfere with the validity of the collected data, especially in applications where statistics are cumulated along a sensor line, such as for an intermittency analysis.

Figures 48a to f show the 'left' and 'right outer interface' probability distributions from 2.0 to 12.0 X/D, at 2.0 D intervals, acquired at the test Reynolds number. The distributions shown represent 5,000 interface locations per 'side' and as such, it must be appreciated that as the wake grows in a transverse sense, the number of possible interface locations increases, and the interface distributions become more irregular due to the diminishing number of samples at each pixel location. Although it was not felt necessary for this comparative study, smoother functions may be accomplished by grouping the results of pixel blocks together, resulting in a loss of transverse spatial accuracy, or by cumulating similar experiments to provide larger population sizes as was demonstrated earlier in Figure 46b. Direct comparisons of the 'outer interface' statistics calculated from the interface distributions of Figures 48a to f, are shown in Figures 49a to d, which present the distribution mean and variance, skewness and kurtosis, respectively, of the interface distributions.

Before examining the 'outer wake' distribution moments in detail, the 'cross-over' extents of the 'left' and 'right' interfaces have been plotted in Figure 50 against downstream location. Also plotted in this Figure are the double shedding frequency component limit locations previously mentioned in section 6.3.2 (indicated as spectral analysis data). The 2.0 and 4.0 X/D location values are likely to be underestimated due to excess light levels in the near-wake region. The function would, nevertheless, suggest that the wake vortices extend across the wake centreline by as much as 1.4 D, between the 4.0 and 6.0 X/D locations, whilst at further locations downstream, the extent of the cross-over region steadily decreases.
Figure 49a shows the mean 'outer interface' location of the wake, with an indication of the variance of the interface location distribution. The values presented are mean 'left' and 'right' results, the interface distributions being very nearly symmetrical, the accuracy of which may be limited due to the relatively small sample population of 5,000 interfaces per 'side'. Figure 49a also shows the equivalent mean and variance values achieved with the imaging technique at a lower Reynolds number of 6.82 * 10^3, corresponding to a freestream velocity of 2.0 m/s, 3.0 to 11.0 X/D, at 2.0 D intervals. The wider transverse wake 'outer interface' extent of the higher Reynolds number flow is clearly illustrated in this Figure.

In order to examine the interface variance with downstream distance more closely, the variance distribution of the test Reynolds number flow has been re-plotted in Figure 49b, which also indicates that the rapid rate of increase of the variance decreases from a downstream location of approximately 4.0 X/D to attain a lower rate of increase between 8.0 and 12.0 X/D. Figures 49c and d show the higher order moment relationship of the 'outer interface' location distribution with respect to downstream location. The skewness distribution in Figure 49c illustrates the degree of advance of the 'outer interface' locations relative to their mean position, and as such, should be an indication of the rate of growth of the wake, which in turn, would be an indication of the rate of entrainment of non-turbulent fluid. The kurtosis relationship with downstream distance plotted in Figure 49d illustrates the degree by which the 'outer interface' location distributions differ from a random, Gaussian distribution, which would have a kurtosis value of zero (flatness factor of 3, section 4.5.2).

In order to examine the consequences of the above-outlined imaging 'outer interface' probability distribution moments, the streamwise component mean velocity profiles presented in Figures 18a to f, have been replotted in Figures 51a to f as normalised mean velocity deficit distributions. The hot-wire
intermittency curves for the corresponding locations have also been shown in these Figures, allowing the direct calculation of wake 'half-distance' ratios. If \( l_o \) denotes half the distance between points on opposite sides of the wake at which the mean velocity deficit is half its peak value, and \( y_o \) is the distance between the wake centre-plane and the half-intermittency point and \( \sigma \) is the standard deviation of the profile of the intermittency factor, then the characteristic ratios \( y_o / l_o \) and \( \sigma / y_o \) may be formed. Previous investigations of self-similar wakes have found these values to be as follows:

<table>
<thead>
<tr>
<th>Source</th>
<th>( y_o / l_o )</th>
<th>( \sigma / y_o )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Townsend (1966)</td>
<td>1.8</td>
<td>0.38</td>
</tr>
<tr>
<td>Thomas (1973)</td>
<td>1.7</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Although the measurement station in the present study is not far enough downstream to ensure a self-similar wake, the corresponding values for the above ratios at 12.0 X/D may be calculated to be:

\[ y_o / l_o = 1.74 \quad \text{and} \quad \sigma / y_o = 0.405 \]

These values are similar to Townsend's (1966) results, the \( \sigma / y_o \) value of 0.21 from Thomas (1973) being more closely related to the equivalent ratio for a jet, rather than to the expected wake ratio.

The half-intermittency locations and peak velocity deficit values shown in Figures 41a to f also allow the entrainment constant, \( \beta \), to be calculated for each downstream location, where,

\[ \beta = \frac{U_o + \frac{1}{2} U_m}{\frac{1}{2} U_m} \cdot \frac{\partial y_o}{\partial x} \]

, as defined in section 2.3.

Whilst the entrainment constant should also only strictly be applied to self-similar wakes, the calculated constants at various downstream locations behind the flat plate are shown in Figure 42, and should serve to indicate the overall trend of the entrainment constant.
The entrainment constant calculated at 12.0 X/D of 0.5, is somewhat higher than the expected value quoted by Townsend (1966) of \( \beta = 0.4 \). As previously mentioned and illustrated in Figure 52, the measuring stations available to the present study were not sufficient to allow measurements in the self-similar wake region, where \( \beta \) may be expected to attain a constant value.

A further hot-wire estimation of entrainment has been achieved through the consideration of the conservation of mass flux within the wake region. For the control volume shown below, the change of mass flux between the two measuring stations \( s_1 \) and \( s_2 \) may be considered to be due to entrainment of irrotational fluid.

\[
\frac{d}{dx} \left[ \int \int u \, dA \right] = E,
\]

where \( E \) is the volume rate of entrainment of ambient fluid per unit length.

Figure 53 shows the mass flux distribution along the wake, the function being normalised against the 12.0 X/D mass flux value. Figure 52 also shows the corresponding distribution of entrainment along the wake with the entrainment being represented as the percentage change in mass flux between the downstream measurement stations.
In order to compare the 'outer interface' mean and variance distributions (Figures 49a and b), these values have been normalised against their values at the downstream location of 12.0 X/D and have been replotted in Figure 53. Although not conclusive, the results presented would seem to imply that there is a correlation between the mass flux distribution and 'outer interface' mean wake location and variance values. Similarly, Figure 49c would seem to indicate that the rate of change of skewness value of the 'outer interface' distribution may also be correlated to the entrainment rate, whilst Figure 49d shows that the 'outer interface' location kurtosis distributions increasingly differ from that of a random, Gaussian distribution, the least difference being recorded at a downstream location of 4.0 X/D.

Sequential wake interface locations, combined with a fixed separation period between fields (20 mS), allows the transverse wake interface velocity and accelerations (expressed in pixels per field period) to be calculated. Figures 54a to c show the distributions of imaging interface velocity and acceleration for downstream locations of 2.0, 6.0 and 10.0 X/D, at the test Reynolds number. Whilst none of these distributions are symmetrical, they have a mean value of zero, indicating that the mean location of the 'outer interface' was stationary (as expected) with respect to time.

Figures 55a, b and c show the variance, skewness and kurtosis distributions of the transverse interface velocity and acceleration between locations 2.0 and 12.0 X/D, at intervals of 2.0 D. The interface velocity and acceleration variance distributions (Figure 55a) closely resemble the interface location variance distribution in Figure 49b. Once again, there would appear to be a good correlation between the interface velocity and acceleration variance functions with the increase of mass flux as shown in Figure 53. The interface velocity skewness distribution (Figure 55b) displays a positive skewness region between limits of 2.0
and 3.4 X/D, indicating a bias towards the wake centreline. At downstream locations greater than 3.4 X/D, the negative skewness indicate a bias towards the irrotational flow and become more constant. The approximate extent of the positive skewness region would appear to be equivalent to the limit of the vortex formation region, and would therefore indicate that the interface velocity distributions within this region are fundamentally different to those of the shed vortices (locations > 3.4 X/D), whilst the acceleration skewness distributions are reasonably constant. Figure 55c shows that the kurtosis distributions follow a similar trend to that of the interface location distribution, that is, an increasing kurtosis with increasing downstream distance.

It is difficult to be more conclusive with respect to the above discussions on entrainment due to the inherent inaccuracies associated with the hot-wire results. (Section 4.5.3 highlighted the difficulties associated with the use of hot-wire anemometers in highly turbulent flows, and in particular, recirculating regions). Hot-wire measurements within 4.0 X/D downstream of the flat plate model are undoubtedly subject to large errors which serve to place doubt on such values as the calculated mass flux and entrainment (at these locations). It is, however, proposed that the trends observed in the results of both the hot-wire and digital imaging techniques may be reasonably compared, especially for downstream locations greater than 6.0 X/D.

Figures 56a to e show the turbulent and 'non-turbulent' intermittency functions (section 5.3.4) achieved using the imaging technique, downstream locations 2.0 to 10.0 X/D, at 2.0 D intervals. Due to the nature of the detection procedure required to formulate the 'non-turbulent' intermittency function, equivalent hot-wire results were, unfortunately, not achievable. Figure 57 illustrates the total 'non-turbulent' intermittency integral as a percentage of the total turbulent intermittency integral. Whilst this relationship cannot be compared directly to the mass flux distribution, the function would appear to be related to the
rate of entrainment of non-turbulent fluid, as previously illustrated in Figure 52. It should be noted that the 'non-turbulent' intermittency function represents the percentage of irrotational fluid within the turbulent wake extent that is available to be entrained. Whilst such a function provides an interesting insight into the fundamental wake structure, it must be appreciated that 'availability to be entrained' does not necessarily equate directly to the percentage of actually entrained fluid. The function would also appear to imply that irrotational fluid that does become entrained, also becomes seeded by smoke, as if this were not the case, the total percentage of 'non-turbulent' intermittency would continually accumulate and increase with downstream distance.

The wake interface statistics discussed during this sub-section revealed some interesting wake characteristics. In particular, the comparison of the hot-wire and digital imaging crossing frequencies highlighted the possibility of detection inadequacy when using single-sensor hot-wire anemometry for turbulence decisions. The digital imaging interface multi-valued distribution would also appear to offer a possible experimental solution to an investigative problem that is restricted by single-sensor Eulerian probes.

It is suggested that the statistical analysis of compressible or stratified flow interfaces could also be accomplished in a similar manner to that discussed in this sub-section, the flow being optically visualized using a Shadowgraph or Schlieren technique. Finally, the various interface location and velocity moments described would appear to be indicative of the entrainment process at a particular flow location, although exact definitions of imaging entrainment rates or constants have not been attempted.
6.3.5 Mean Fluctuating Turbulence Quantities

Mean fluctuating turbulence quantities were undertaken using image intensity fluctuation analysis and traditional hot-wire techniques. Figures 58a to f show comparative distributions of turbulence intensity achieved using the hot-wire anemometer and r.m.s. pixel intensity fluctuations, the functions being normalised by their respective centreline values. The hot-wire turbulence intensity distributions are 'combined intensity' (replotted from Figures 18a to f) and the zonal 'turbulent component' intensity data, section 6.2.4. As previously defined in section 4.5.2, 'combined' hot-wire results were obtained by combining turbulent and non-turbulent zonal measurements, this being equivalent to a standard continuously sampled hot-wire turbulence intensity measurement. The distributions of r.m.s. pixel intensity, Figures 58a to f, appear to indicate that at locations greater than 6.0 X/D there is a fair correlation between the mean turbulence intensity and fluctuating pixel intensity. At locations 2.0 and 4.0 X/D this correlation is not evident, the transverse extent of the functions being very much less than the indicated turbulence intensities. It should, however, be appreciated that the hot-wire turbulence intensity distributions themselves are in error at these latter locations (see sections 4.5.3 and 6.2.4) and may only be identified as approximate functions. The reduced turbulence intensities determined at 6.0, 8.0, 10.0 and 12.0 X/D should, however, be more accurate. To understand why the pixel intensity fluctuation results at 2.0 and 4.0 X/D differ so markedly from those between 6.0 and 12.0 X/D, it is again necessary to refer to the physical quantities that were measured.

The pixel intensity fluctuations were calculated directly from observations of the illuminated wake. In order to calculate an accurate r.m.s. value, it is necessary that all of the pixel intensities fall between the resolvable limits of the imaging sensor system. As previously discussed in section 6.3.1, the light intensities in the near-wake
(locations < 4.0 X/D) of the model were much higher than the resolvable limit of the sensor, requiring the video camera lens aperture to be partially closed. It is this requirement that causes the discrepancies between the imaging results at 2.0 and 4.0 X/D, compared to the results obtained between 6.0 and 12.0 X/D, where the full range of light intensities could be adequately resolved. Accepting that the imaging results at downstream locations of less than 4.0 X/D are in error, it would seem appropriate to discuss the results obtained between 6.0 and 12.0 X/D in more detail.

The r.m.s. pixel intensity fluctuations have been derived from visualized images in which, if turbulent flow is present values greater than zero are recorded, and if non-turbulent flow is present intensity values of zero are recorded. In contrast, a hot-wire anemometer records both turbulent and non-turbulent velocity fluctuations for a mean turbulence intensity value, whereas the imaging technique records no fluctuations within the irrotational flow. In order to compare the 'turbulent only' turbulent intensities the zonal distributions have also been plotted in Figures 58a to f, but would appear not to be well correlated to the pixel intensity distribution. This may be explained by considering that whilst the irrotational flow contributions in terms of pixel intensity were zero, the number of zero encounters has still been employed in the calculation of the sample size and hence, mean pixel intensity value.

In considering the mean turbulence intensity distribution it may be observed that where the r.m.s. pixel intensity distribution reaches a value of zero (indicating no turbulent flow at that location) the hot-wire anemometer still registers a finite turbulence intensity due to the flow fluctuations within the irrotational fluid. In order to try and examine more accurately comparable functions, the hot-wire mean turbulence intensity distributions shown in Figures 58a and f have been adjusted by deducting a percentage of this irrotational flow turbulence intensity. This correction consisted of multiplying the wake limit
turbulence intensity value (as indicated by the velocity higher order moments and digital imaging intermittency zero values), by \( (1-Y) \), where \( Y \) is the turbulent intermittency factor at the location considered. The corrected hot-wire turbulence intensity profiles shown in Figures 59a and b, for downstream locations 6.0 and 10.0 X/D, are well correlated with the r.m.s. pixel intensity distributions, the finite differences between the functions being of comparable magnitude to the degree of experimental inaccuracy associated with the measured values. The deduction to be tentatively drawn from these results is that the degree of r.m.s. fluctuations of light intensity across the visualized model wake may be directly related to the degree of r.m.s. velocity fluctuations. The results are, however, not sufficient to indicate whether the contributions of the fluctuations are themselves directly related, such as high light intensities for high turbulence and low light intensities for low turbulence levels. It would be suggested that only careful conditional sampling techniques would be able to attempt this particularly precise comparison.

Figure 60 shows the centreline turbulence intensity rate of decay compared against the r.m.s. pixel intensity fluctuation rate of decay, over the range 6.0 to 12.0 X/D. Although by no means conclusive, Figure 60 would appear to indicate that the rate of decay of the centreline r.m.s. pixel fluctuations is also similar to that of the turbulence intensity measurements, thus re-affirming the aforementioned correlation between pixel r.m.s. fluctuations and turbulence intensity.

The combination of the findings of the pixel intensity fluctuation investigations would appear to offer the possibility of global turbulence intensity analysis using smoke flow visualization combined with limited hot-wire anemometry. For instance, the turbulence intensity distributions between locations 6.0 and 12.0 X/D could have been predicted from the r.m.s. pixel intensity fluctuations
and a single measurement of turbulence intensity using a 
hot-wire anemometer at the centreline location of 6.0 X/D. 
More accurate distributions would, of course, be 
accomplished through establishing a complete centreline 
turbulence intensity profile from 6.0 to 12.0 X/D, and 
undertaking the digital imaging analysis using these more 
complete normalising values. In order to apply the 
corrections for the irrotational turbulence intensity 
components, it would also be necessary to assume an 
intermittency function distribution and an appropriate 
irrotational turbulence intensity value. Formation of a 
suitable intermittency function would, however, be 
comparatively simple, as the digital imaging technique 
produces this function on-line (as demonstrated in section 
6.3.1) and would, of course, be available at the data 
analysis stage of any investigation.

The primary advantage that the digital imaging turbulence 
intensity analysis procedure would offer is that of 
experimental expedience. As has been mentioned throughout 
this comparative study discussion, the digital imaging 
technique simultaneously acquires 512 data points from 
within the flowfield, realising a tremendous time saving 
over traditional single-location flow sensors.

Further discussion on the factors relevant to applying this 
and other digital imaging techniques to a complete two-
dimensional flow image, rather than the single-line mode of 
the present study, is undertaken in the following section of 
this chapter.

6.4 System Expansion into Two Dimensions

The previous section of this chapter has discussed the 
results of the digital imaging technique through direct 
comparisons with hot-wire anemometry data and has shown that 
flow visualization images may be successfully analysed to 
yield quantitative flow information. Without referring
directly to any particular digital imaging analysis procedure (intermittency, turbulence intensity, etc.) it would appear evident that the possible benefits offered by the single-line, one-dimensional nature of the present investigations could be multiplied manyfold through the simultaneous analysis of many single-lines from an illuminated two-dimensional flow plane. The only limitation on the capabilities of such a technique would initially appear to be the restricted computational speed of the digitising and analysis systems.

The computational restrictions may be demonstrated by considering the present system's pixel access time, which as previously detailed in section 3.4, has a quoted average value of 800 nanoseconds. Without any allowance for computational overheads, the pixel access time alone would allow a theoretical maximum of 49 image lines (512 pixels per line) to be accessed per image field. After an allowance for the image analysis routines required to compute the various flow statistics, real-time image analysis would be limited to only a few lines (less than 10 perhaps) of the image. This, however, is not a major concern as the ever-increasing capabilities of digital imaging hardware and the advent of commercially affordable parallel processors and 'transputers' will undoubtedly be combined in the near future to overcome any such processing limitations. Indeed, from a purely computational viewpoint, it would now be possible to design and construct a real-time image analysis system capable of providing highly detailed global flow statistics (such as those previously discussed in this chapter), which would examine 256 lines of a visualized flow with 512 data points per line. Such a system would analyse 6.5 million flow locations per second and produce complete global flow statistics in a matter of minutes. The computational requirements are, however, not the only system components that must be overcome in order to realise a two-dimensional flow diagnostic facility. Having established that the data may successfully be analysed, it is necessary to establish how such data may also be visually acquired.
The comparative study discussions in section 6.3 have emphasized the problems encountered with varying light levels within an image field. In brief, the limited dynamic range of an image sensor dictates that high light levels which fall outside the upper sensor limit must be reduced either by restriction via a variable lens aperture (manual camera) or through appropriate compensation circuitry (automatic camera). Any degree of light attenuation causes very low light levels to be lost which, as demonstrated in section 6.3, unduly affects the statistical values obtained through subsequent analyses. It may, therefore, be deduced that any global, two-dimensional visualization system will be dependent on the range of light intensities present falling within the desired image, the accuracy of any resulting analyses directly reflecting the sensor's ability to resolve these light levels. Unfortunately, video imaging systems have been designed primarily to suit human perception requirements and not as dedicated image analysis tools. It would seem unlikely, therefore, that an image sensor system with a theoretically optimum sensitivity range to facilitate such a variation in image intensities will ever be produced commercially.

In addition to the imaging requirements, it should also be appreciated that the illumination facilities must be vastly improved to achieve a complete, two-dimensional laser 'sheet' visualization. The present study illumination facility used a 5 mW Helium-Neon laser, this device being compact, relatively rugged, inexpensive and requiring only limited special safety considerations. Complete flowfield visualization via a laser sheet is best achieved using a multi-faceted rotating mirror assembly (similar to that described in section 4.6.3). A typical visualization system of this nature would typically utilise an Argon-based laser with a rated power output of the order of 4 W. Such a laser facility is large and somewhat cumbersome, relatively expensive and requires special safety precautions. From a practical viewpoint, many research establishments may not be in a position to afford a 4 W laser, whilst a 5 mW He-Ne
laser would be well within any laboratory's means. Those establishments that are fortunate enough to possess such a laser may, of course, implement sheet visualization without great difficulty or further expense.

The above discussions on the extension to a two-dimensional analysis system may be summarised by emphasizing that although real-time image analysis may be expanded via a laser sheet illumination system, the increase in system component costs could be significant. In addition, it may be necessary to develop an imaging sensor with a wide dynamic range capability in order to resolve the range of light intensities generally encountered within turbulent wake flows. Having accomplished a suitable 'front-end' to the two-dimensional image analysis system, the high computational speeds required to facilitate complete field analyses could be relatively simply developed through dedicated imaging hardware using either single-board computers (SBC's), transputer technology or array processing. Having accomplished this primary development, future system enhancements could then realise the implementation of higher sensor framing rates with, perhaps, partial-framing or sub-sampling capabilities, and increased spatial resolution. Such system developments will undoubtedly be achievable providing the demand and encouragement for such an exciting undertaking is forthcoming.
6.5 Summary

This chapter has characterised the principal flow parameters associated with the two-dimensional flat plate model and established that these characteristics were unaffected by the smoke-visualization system. The major undertaking of this chapter was, however, a detailed comparison of hot-wire and digital imaging statistical wake data. Whilst both excessive and very low image intensities proved to be a restriction to the imaging system's use, generally good agreement for all of the presented data was found. Detailed discussions have revealed excellent imaging capabilities for intermittency analysis, autocorrelation functions and spectral analyses, spatial correlations, wake interface data plus a possibility of turbulence intensity extraction.

Finally, the possibility of expanding the imaging analysis procedures into two dimensions was discussed, with cautionary warnings being expressed with regard to large variations in image intensity. Whilst comparisons of the digital imaging statistical data have been reported as individual sub-sections within this chapter, it should, perhaps, be re-emphasized that all of the information required to produce such statistics may, where applicable, be simultaneously acquired during a single digital imaging experiment.

The next chapter of this thesis illustrates further applications of the digital imaging technique to alternative flow models and details a variety of digital imaging approaches, related to both smoke, vapour-screen and liquid crystal flow visualization techniques.
CHAPTER SEVEN

FURTHER DIGITAL IMAGING APPLICATIONS

7.1 Introduction

The digital imaging analysis technique has been carefully investigated through a series of comparative studies (Chapters 4, 5 and 6). These comparative investigations used hot-wire anemometry results to explore characteristic statistical functions associated with the turbulent wake of a thin, two-dimensional flat plate model. Direct comparisons made between the hot-wire and digital imaging results indicated the capabilities of a real-time image analysis system with respect to smoke flow visualization experimentation. The results obtained have produced good correlations between intermittency functions, vortex shedding frequencies, spatial correlation lengths, crossing frequencies with further promising indications in the region of turbulence intensity. The developed imaging system is, however, by no means limited to the study of turbulent flat plate wakes, and in this chapter, further applications of the quantitative digital imaging technique are reported, the particular investigations involving secondary vortex shedding from a circular cylinder and an intermittency analysis of a turbulent jet issuing into a uniform crossflow.

In addition to the above-mentioned quantitative results, the imaging hardware (IP-512 system) was also employed to perform specific image processing functions, which were utilised to provide digitally enhanced flow visualization images. Such enhancement techniques often help to reveal flow details that are not immediately visible within an original image and include options such as pseudo-colouring and edge enhancement. This chapter, therefore, outlines the image processing algorithms incorporated into the digital imaging system and provides application examples of their use with preliminary studies of various flow models.
In particular, the investigated flow models include:

(i) a flat plate boundary layer modified through passive drag reduction elements (LEBU's),
(ii) dynamic stall on an aerofoil, and
(iii) the use of an illuminated vapour-screen technique for supersonic flow visualization.

The latter of these listed topics includes details of a recent digital imaging hardware enhancement which has enabled the implementation of real-time image processing in vapour-screen visualization experimentation. The hardware necessary to perform such real-time functions included a pipeline processor, capable of undertaking wholefield logical image operations which, combined with a real-time histogram module, provided a powerful, monochrome, real-time imaging system. Further recent investigations have also enabled preliminary data to be gathered from a true-colour video digitising environment, this being:

(iv) the quantification of shear stress sensitive liquid crystals.

Whilst this topic is discussed only from a preliminary viewpoint, the suggestions made are indicative of the Author's opinion that a real-time true-colour video digitising system may be successfully applied to the quantification of global shear stress values using liquid crystal visualization.

Throughout the following sections, experimental and measurement details are limited to a brief, yet concise description of the study in hand, allowing each investigation to be discussed in an effectual and precise manner. Where possible, sketches within the text have been used instead of detailed Figures in order to aid this aim.
The individual sections of this chapter are as follows:

7.2 Digital Image Processing,
7.3 Secondary Vortices from a Circular Cylinder,
7.4 Jet Issuing into a Crossflow,
7.5 Boundary Layer Modification by Passive Means,
7.6 Dynamic Stall on an Aerofoil,
7.7 Vapour-Screen Visualization, and
7.8 Shear Stress Sensitive Liquid Crystals.

Before embarking upon descriptions of the above-mentioned experimentation, the following section will introduce the image processing concepts and algorithms used throughout the remaining sections of this chapter.

### 7.2 Digital Image Processing

The descriptive title 'digital image processing' encompasses a very wide range of digital imaging techniques, all of which perform specific processing functions and are designed to fulfill precise imaging requirements. An excellent overview of digital image processing has been produced by Pratt (1978) and Readers interested in various aspects of image processing such as image restoration, geometric distortion and morphological definitions, etc. should refer to this and Hall's (1979) book. The discussion in this section is limited to the image processing functions relevant to the present flow visualization application studies and thus only incorporates aspects of grey level image enhancement and feature extraction (aspects of true-colour video digitisation are dealt with specifically in section 7.8). The majority of the algorithms and images presented within this chapter were processed under software control, although some real-time image processing functions have also been implemented (section 7.7).
From a general viewpoint it may be assumed that image enhancement techniques include:

(i) Pseudo-colour Display,
(ii) Noise Cleaning,
(iii) Edge Crispening, and
(iv) Contrast Enhancement.

Whilst feature extraction techniques include such topics as:

(i) Histogram Features, and
(ii) Edge Features.

The nature of digital image processing dictates that most processing functions require complex calculations and must inevitably transform an original image array into a processed image of different intensity values. Whereas the digital image analysis technique previously discussed in Chapters 4, 5, and 6, analysed data in real-time, complex image processing routines demand a 'recorded' original image and may require a number of seconds to perform any one particular function. A complete processing application may require many such individual transformation functions, and normally includes a degree of interactive operator initiative. The image processing system features relevant to the remaining experimental studies within this chapter are discussed in the following sub-sections:

7.2.1 Image Acquisition and Storage, and

7.2.2 Image Processing Algorithms.

To demonstrate the elements outlined in these sub-sections, both 'raw' and enhanced visualization images of the flow behind the two-dimensional flat plate model have been included. The flat plate flow images were visualized by a 'lamp and slit' illumination technique illustrated in the following sketch, the resultant wake visualization being a wedge of illuminated smoke (not a two-dimensional sheet).
The resulting images may be regarded as providing only qualitative flow details, but nevertheless reveal very interesting flow structures.

7.2.1 Image Acquisition and Storage

The digital imaging hardware has been previously described in section 3.4 of this dissertation. The objective of this sub-section is to describe the principal methods by which the flow visualization images were acquired and stored, and it is assumed that the Reader is familiar with the details of the basic hardware modules incorporated in the IP-512 imaging system (an enhanced imaging hardware configuration incorporating a pipeline processor, being detailed in section 7.7 of this chapter).

The two frame buffers (FB-512) within the imaging system each offer 256 kilobytes of digital frame storage. A single imaging frame buffer may contain either one 512 * 512, two 512 * 256, or four 256 * 256 pixel resolution digital images, depending on the acquisition mode selection of the analogue processor board (AP-512). In the 256 * 256 pixel or 'quarter-frame' mode it is possible to store four individual images (either sequential or temporally separated) into each frame buffer.
The real-time operation of the imaging boards enabled eight sequential quarter-frames to be directly stored, the timing interval between each image being controllable from 20 ms (standard video rate, 50 Hz) to seconds, minutes or even hours depending on the application requirements. The following sketch illustrates the sequential frame buffer storage organisation adopted for a typical image sequence in quarter-frame mode:

![Frame Buffer Organization](image)

Plate 8 shows a single 256 * 256 raw image field of the flow behind the flat plate model, plus a sequence of four such raw sequential fields (sequence 1-4, Frame Buffer 0).

Having acquired a series of images, it is possible to store them either to 'hard' or 'soft' storage devices (disks), or replay them as a real-time or 'slow motion' movie (using forward or reverse sequencing). The soft or 'floppy' RX50K diskette storage capacity of 400 kilobytes (single-sided, double-density) allowed six quarter-frame, three half-frame or 1.5 full-frame images to be stored per diskette, whilst the 31.0 megabyte capacity Winchester 'hard' disk allocated 1.0 megabyte of free memory with the storage of every four full-format (512 * 512) images. All image data stored to disk was transferred as 'unformat ted' information, formatted files requiring almost 1.5 times more storage allocation. The computing system convention adopted for these studies used floppy diskettes as the primary storage media, picture files being copied onto the hard disk only when required for image processing or repeated display purposes.
7.2.2 Image Processing Algorithms

All of the image processing routines described in this subsection (and all image processing examples presented in this chapter) were written exclusively for the Micro PDP11/73 system by the Author. As for previous programming requirements, general functions such as file management, terminal I/O and complex arithmetic programme operations were written as Fortran 77 code, the data I/O, time-critical pixel manipulations and transformations being written in Macro II (machine-code assembler). Although more elaborate image processing systems may offer some real-time hardware-based image processing functions (see section 7.7), the following software algorithms were applied to frame buffer resident, stored images (which may be transferred to disk) and in general took approximately five to ten seconds to perform. Due to the nature of the quarter-frame acquisition requirements the default format for the software-based image processing functions was chosen to be 256 * 256 pixels, although other format images could also be selected.

The image processing algorithms outlined in this section are restricted to those most frequently applied to the visualization images found in this chapter, a more detailed account of these and other processing functions may be found in Pratt (1978) and Hall (1979). Whilst all of the digital image analysis technique routines described in the foregoing chapters of this thesis dealt exclusively with individual pixel intensity values, image processing algorithms require image manipulations that incorporate the examination of pixel groups. In general, pixel group processing changes the spatial content of an image by looking at the region around an individual pixel to determine the brightness trends within the image, with operations being conducted through 'convolutions' or 'masks'.

A typical spatial convolution calculates a weighted average of intensities around and including each image pixel. The size of the convolution kernel (that is, the two-dimensional
array that has the target pixel at its centre) determines the area over which brightness trends will be examined in each operation. In a 3-by-3 convolution, for example, the kernel consists of a square of nine pixels with the target pixel at the centre. Convolutions may be square arrays of basically any dimension but are normally limited to, say, 3-by-3 pixels as they are extremely arithmetic-intensive. Basically, a convolution multiplies each pixel in a given kernel by a coefficient, to produce a weighted average of the resulting values. The coefficients determine the characteristics of the convolution and may differ for each pixel in the kernel. The sketch below illustrates a typical convolution transformation process.

High-pass filters, for example, make high-frequency information more prominent. Since rapid changes in intensity are associated with details, edges, or textures, high-pass filters make small variations in an image easier to see. A coefficient mask like that shown below is a typical implementation for a 3-by-3 high-pass filter.

\[
\begin{bmatrix}
  -1 & -1 & -1 \\
  -1 & 9 & -1 \\
  -1 & -1 & -1 
\end{bmatrix}
\]
Low-pass filters attenuate high-frequency information and, thus, reduce detail and tend to blur image edges. They can remove noise from an image, or diminish detail features to make the overall shape of objects more apparent. A typical coefficient mask for a low-pass filter weights each pixel equally as shown below.

\[
\begin{bmatrix}
1 & 1 & 1 \\
1 & 1 & 1 \\
1 & 1 & 1
\end{bmatrix}
\]

Laplacian edge enhancement also makes high frequencies prominent whilst severely attenuating low frequencies, making such an enhancement very good at locating object boundaries. A Laplacian mask may have the following form.

\[
\begin{bmatrix}
1 & -2 & 1 \\
-2 & 5 & -2 \\
1 & -2 & 1
\end{bmatrix}
\]

Relative image intensity gradients may also be highlighted by a Sobel gradient mask, which combines edge with detail detection. The Sobel convolution shown below is extremely instruction-intensive as it requires the square-root of the resultant pixel summation.

\[
\begin{bmatrix}
-1 & 0 & 1 \\
-2 & 0 & 2 \\
-1 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
1 & 2 & 1 \\
0 & 0 & 0 \\
-1 & -2 & -1
\end{bmatrix}
\]

where, the resultant pixel transformation = \( \sqrt{x^2 + y^2} \)

In addition to the above algorithms, pseudo-colouring of the visualization images has also been widely employed where the limited grey-scale identification capabilities of human vision may be artificially improved through the assignment of various colour combinations to a range of specified grey levels. These assignments are made through output table programming (R, G, B Look-Up-Tables), and do not require any pixel value modifications.
Where pseudo-colour assignments have been directly given to an original grey-scale image, an indication of the relative grey level values associated with the different colour ranges has been provided.

In order to demonstrate some of the above features, further examples of the flat plate wake flow have been included. Plate 9 shows eight sequential fields of the flat plate wake, the vortex shedding structures being highlighted through a Laplacian thresholded filter which has accentuated the wake interface outlines. A pseudo-coloured enhancement of Plate 9 is shown in Plate 10, demonstrating clearly how much easier it is to identify structure intensities through colour discrimination rather than having to rely on grey-level interpretations. Plate 11 shows fields 1 and 2 of Plate 10 displayed at full screen resolution (zoomed display), the actual image format still being 256 * 256.

It must, however, be emphasized that image enhancement techniques applied to visualization pictures are generally used to improve their 'image quality' for human viewing. Since human judgement is not as globally reliable as quantitative statistical results, the 'quality' of the visualization images may appear significantly different to individual Readers, depending on that individual's own conceptual preferences. Whilst complex digital manipulations may be achieved in order to try and 'improve' an image for human recognition, it should always be appreciated that the one true representation of the visual data remains quantified only in the original image matrix pixel values.

Having introduced the general image processing concepts, the following sections will examine the additional experimental models using either quantitative image analysis techniques and/or the above-outlined digital image enhancement procedures. Further real-time modifications to the imaging capabilities are outlined in section 7.7 which examines a real-time image enhancement technique.
7.3 Secondary Vortices from a Circular Cylinder

The periodic shedding of vortices from circular cylinders has been studied for over a century. In the early sixties, Bloor (1964), conducted an important study on the transition to turbulence of a circular cylinder wake flow and observed an instability phenomenon, which she termed 'transition waves'. In later dye-visualization studies, Gerrard (1978) reported what he termed 'knots' and 'fingers' which regularly appeared in the cylinder near-wake region. Further high-speed cinematographic visualization of a similar effect was reported by Bernal (1981) who analysed his film using frame by frame sequence playback. In his study, contiguous hairpin-type vortices were found to 'ride' on and around essentially two-dimensional mixing-layer vortices. Recently, Wei and Smith (1986) used high-speed videography of hydrogen-bubble visualizations together with hot-wire measurements to study the characteristics of the circular cylinder secondary vortices. Through a quantitative study involving visualization analysis and hot-wire measurements, Wei and Smith found the dependence of the non-dimensional shedding frequency $f_1/f_v$ on Reynolds number, $Re_d$, to be,

$$f_1/f_v \propto (Re_d)^n$$

where, $f_1$ is the secondary vortex shedding frequency,
$f_v$ is the Strouhal vortex shedding frequency, and
$Re_d$ the Reynolds number based on cylinder diameter.

Wei and Smith (1986) established that this non-dimensional shedding frequency demonstrated a 0.87 power-law relationship relative to Reynolds number. Bloor (1964) had previously suggested a 0.5 power-law value for such a relationship but Wei and Smith re-examined her data and claimed a 0.83 power-law relationship when 'lumping' all of her data into a single function. The flow visualization studies conducted by Wei and Smith involved simultaneous image acquisition from orthogonal viewing directions. These pictures were reviewed using single-frame advance techniques.
and suggested that the secondary vortices tended to interact with the Strouhal vortices as illustrated below.

Wei and Smith (1986) concluded that the rapid distortion of secondary vortices into cellular structures within the cylinder near-wake region appeared to result in a strong spanwise mixing, which they suggested may be the mechanism of transition from laminar to turbulent Strouhal vortices. A typical sketch of their side-view visualizations is shown below.
Attempts by Wei and Smith (1986) to quantify the frequency of the secondary vortices using a hot-wire anemometer met with only limited success. Their investigation highlighted the complications involved in using a stationary hot-wire sensor to detect vortices which are essentially developing in both time and space. The nature of this shedding phenomenon dictated that the anemometer sensor detected the secondary vortices only intermittently, making a subsequent frequency analysis very difficult (ideally conditional upon the Strouhal vortex location). Such a problem may be eloquently described as trying to study a Lagrangian (developing in both space and time) phenomenon using an essentially Eulerian (stationary sensor) probe. It was this difficulty that initially inspired the investigation of the secondary vortex phenomenon using the digital imaging technique, as this visual analysis method was not restricted to single-location measurements.

In order to investigate secondary vortex frequencies a two-dimensional circular cylinder model was constructed from polyvinyl chloride (PVC). The model was formed from a smooth surface hollow tube, having an internal diameter of 38.1mm (1.5 inches) and an external diameter of 42.5mm, Figure 61. The model spanned the 0.75m height of the working section (located by cast acrylic rings and projecting through the tunnel roof and floor), representing an area blockage ratio of 6.81 percent. Smoke was injected directly from the model into the wake region through a number of 1.5mm holes, spread over a 30.0mm extent of its central span, 40 degrees either side of the model centreline. The smoke was introduced into the model core through a 21.5mm (O.D.) copper tube, which was sealed at one end and perforated around 360 degrees with 1.5mm diameter holes over a 25.0mm extent of its central span. The tube was centralised and located within the cylinder model by three cast acrylic rings, two of which incorporated rubber seals to restrict the smoke to an adjustable central volume.
Initial investigations of secondary vortex shedding consisted of full-field flow visualizations. The illumination for these experiments was provided by a simple exterior lamp/slit combination which illuminated a wedge-shape section of the wake region as illustrated below:

The freestream velocity for the visualization experiments was restricted to 1.0 m/s, Reynolds number of $2.85 \times 10^3$, in order to allow a sequential visualization of the secondary vortices at the standard video framing rate of 50 fields per second. Initially, however, the general shedding process behind the cylinder model was visualized using the illumination configuration (shown above). Plate 12 shows two original sequential images (numbers 1 and 2) together with their Sobel-operated versions to accentuate the image light intensity gradients. A complete sequence of eight pseudo-coloured images is shown in Plate 13, with Plate 14 showing a zoomed version of an individual image (number 1). These images illustrate the well known aspect of vortex shedding from a circular cylinder very clearly. A more detailed examination of the wake vortex formation region revealed the presence of secondary vortices, Plate 15 showing four sequential and pseudo-coloured original images. Plate 16 shows a Sobel-operated version of Plate 15, together with a single zoomed Sobel-operated image (number 4) from the sequence.
The image sequence in Plate 15 would appear very similar to the visualizations presented by Wei and Smith (1986), the increased framing rate achieved by these Authors (120 frames per second) enabling values of secondary vortex shedding frequencies to be quantified (counting vortices in a given number of frames) directly from their recorded image sequences. Plates 18 and 19, showing the Sobel-operated images, would appear to define the structure of the individual secondary vortices more clearly than the original 'raw' images and also appear to indicate some three-dimensionality of these vortices in the transverse (into picture) direction. When replayed as a 'movie' sequence using the computer display facility it was possible to witness the development and downstream progression of the secondary vortices quite distinctly. Due to the simplistic lighting arrangement for the above visualizations, the right half of these images, Plates 17 to 20, appears well lit and detailed, whilst the left half of the images is rather poorly illuminated. Having demonstrated the existence of the circular cylinder secondary vortices, an attempt to quantify their frequency was undertaken using both the digital imaging technique and hot-wire anemometry. The digital imaging technique was configured so that the cylinder wake was illuminated transversely (Y-direction) at the model mid-span as illustrated below:
The expected secondary and Strouhal vortex frequencies were initially predicted from the measured cylinder Strouhal number and Wei and Smith's (1986) relationship, previously quoted as:

\[ \frac{f_i}{f_v} = \left( \frac{Re_d}{470} \right)^{0.87} \]

In order to establish the cylinder Strouhal number, the Strouhal shedding frequencies were identified using both the imaging technique and hot-wire anemometry. Figure 62 shows the shedding frequency relationship over a freestream velocity range of 1.0 to 8.0 m/s, corresponding to Reynolds numbers (based on cylinder diameter) of between \(2.85 \times 10^3\) and \(2.28 \times 10^4\). Excellent agreement was achieved between the two techniques which revealed an uncorrected Strouhal number for the cylinder of 0.204. Combining this Strouhal number value with Wei and Smith's non-dimensional shedding frequency relationship inferred that the expected secondary vortex shedding frequencies would exceed the 25 Hz Nyquist frequency of the digital imaging system at a Reynolds number of approximately \(2.8 \times 10^3\), corresponding to a freestream velocity of 1.0 m/s. Combining this upper limit with the smoke tunnel's lowest constant freestream velocity, revealed that the digital imaging experiments could only be conducted over an approximate and somewhat restricted freestream velocity range of 0.7 to 1.0 m/s, corresponding to a Reynolds number range of 2.00 to \(2.85 \times 10^3\).

Digital imaging shedding frequencies were analysed with the illuminating beam at downstream locations between 1.0 and 3.0 D. At the 3.0 D downstream location only the Strouhal vortex shedding was detected, whilst at 1.0 and 1.5 D both Strouhal and secondary vortices were evident in frequency analyses. Figure 63 shows an autocorrelation function and associated spectral analysis at the 1.5 D location, for a freestream velocity of 1.0 m/s, Reynolds number \(2.85 \times 10^3\). Similar results were obtained at freestream velocities between 0.7 and 1.0 m/s, at 0.1 m/s intervals.
To confirm the digital imaging analysis results, attempts were undertaken to identify the secondary vortex frequencies using hot-wire anemometry. Identification of secondary vortex frequencies was, however, found to be very difficult, the exact positioning of the hot-wire sensor within the flow being of paramount importance to a successful frequency determination. The most expedient probe positioning technique was eventually found to involve aligning the hot-wire sensor with the mean outer interface wake location of the vortex formation region, as revealed through simultaneous smoke flow visualization. The hot-wire results confirmed the digital imaging technique results at the appropriate Reynolds numbers and, in addition, provided further secondary vortex frequencies at freestream velocities of 1.50 and 1.75 m/s, corresponding to Reynolds numbers of 4.3 and 5.0 * 10^3. Figure 64 shows a hot-wire autocorrelation function and spectral analysis obtained at 1.50 m/s, Reynolds number 4.3 * 10^3.

Although limited in Reynolds number range, the combined digital imaging and hot-wire secondary frequency results have been plotted against freestream velocity in Figure 65, together with Wei and Smith's (1986) predicted curve. These frequencies have been replotted in Figure 66 using log axes, as non-dimensional shedding frequency (f_i / f_v ) against Reynolds number. Although the results of the digital imaging and hot-wire analyses do not immediately appear to obey the predicted relationship obtained by Wei and Smith, the degree of spread of the results is of a similar order to that reported in both Wei and Smith's and Bloor's (1964) experiments. Unfortunately, the limited nature of this investigation precludes further conclusions being drawn from this data set, but would nevertheless appear to indicate a possible means by which secondary vortex frequencies may be studied in more detail, using perhaps, a CCD 'intelligent' video sensor, at partial-framing rates of the order of 1.0 to 2.0 kHz. Utilisation of an improved imaging system of this nature would appear to offer a very expedient method of determining an accurate non-dimensional shedding frequency.
relationship over a Reynolds number range of approximately \(2.0 \times 10^3\) to \(2.5 \times 10^4\) (using the present experimental configuration) and, of course, over other Reynolds numbers for cylinders of different diameter. Such a method would appear to be very much less complicated and hence, far less time consuming than an attempt to apply single-location probe technology to the same problem.

The process by which the cylinder wake was visualized involved the injection of smoke contaminant directly into the model's base region. This injection of fluid represented a possible base-bleed contribution and depending on its volumetric flowrate could, itself, influence natural base pressure region fluctuations and hence, the vortex formation and shedding processes (section 2.3). In order to investigate the influence of small degrees of 'excess' base-bleed into the model's wake, the digital imaging technique was employed to monitor the frequencies of both the Strouhal and secondary vortices. In relation to this study, it should be noted that secondary vortices may be hypothesized to be the result of free-shear instability amplification in the separated cylinder boundary layer. On the other hand, the generation of Strouhal vortices involves not only the vorticity in the separated boundary layer, but also the effect of fluctuating base pressure, this interdependence distinguishing the origin of Strouhal vortices from the supposedly 'simpler' origin of secondary vortices. Wei and Smith (1986) formed an alternative description which suggested that the secondary and Strouhal vortices were instabilities of different wavelengths which evolved somewhat independently from the same shear layer, but via different processes.

The base-bleed experiment consisted of varying the smoke contaminant injection rate into the model wake by varying the centrifugal smoke pump voltage. Figure 67 shows a typical shedding frequency relationship with smoke pump voltage, the experiment being conducted at a nominal freestream velocity of 1.0 m/s, Reynolds number \(2.85 \times 10^3\).
The bleed results would appear to indicate that small variations in base-bleed rate produced relatively significant changes in secondary vortex frequency (18.1 to 19.6 Hz) whilst the Strouhal vortex frequency remained comparatively constant at 4.9 Hz. These results were typical for all of the experiments conducted with the digital imaging technique and, although limited in investigative detail, would appear to illustrate one particular characteristic of secondary vortices. Namely, that the formation of secondary vortices does not have a 'simple' origin within free-shear layer instabilities, but instead, is also dependent on base pressure characteristics.

Although the above results and discussions are only of a preliminary nature it would appear that the study of secondary vortex instabilities should, perhaps, be further undertaken with respect to both the quantitative digital imaging technique and digitally enhanced flow visualization experiments. In addition, a further demonstration of secondary vortex dependence on base pressure could perhaps be assisted by a more thorough investigation of the influence of base-bleed and/or splitter plates. It should, perhaps, also be suggested that as secondary vortices are sensitive to shear layer instabilities, the very presence of an intrusive probe, such as a hot-wire sensor, into a model shear layer could itself adversely affect the phenomenon under study, and should therefore be fundamentally avoided if alternative measurements were available. This would, of course, be adequately achieved through the use of non-intrusive measurement techniques such as those offered by flow visualization (optical or seeded). Using an alternative illumination procedure, it may also be possible to characterise the transverse, three-dimensional nature of these secondary vortices using spatial correlation analyses in a similar manner to the longitudinal experiments previously reported in section 6.3.4.
7.4 Jet Issuing into a Crossflow

This study has tentatively investigated a jet issuing into a crossflow configuration to further demonstrate the applicability of the digital imaging technique to the analysis of complex three-dimensional turbulent flows. This investigation is, however, of a preliminary nature and does not constitute a critical investigation of the flowfield.

The interaction between a jet and a crossflow may be found in many branches of engineering. Examples such as fuel injector flows, stack emissions and effluent disposal are not uncommon, although the principal region of interest is to applications involving V/STOL aerodynamics and jet steering systems capable of manoeuvring combat aircraft at high angles of attack. Indeed, the application of the digital imaging technique to this particular flow model was inspired by a study of this flow configuration presently being conducted in the Department of Civil Engineering (boundary layer tunnel).

The principal features of a jet in a crossflow configuration are sketched below.
The main flow characteristics are the curvature of the jet into the freestream direction, combined with an increasing jet expansion with downstream distance due to entrainment. The shape of the jet changes from an initial circular cross-section to a 'kidney' shape dominated by two counter-rotating regions of streamwise vorticity, or vortices. There is a decrease in maximum jet velocity with downstream distance and external to the jet, vortices are shed from the jet sides, in a similar manner to those vortices shed from a solid cylinder placed in a crossflow. The jet velocity centreline trajectory is dependent upon the ratio of the jet and freestream velocity and has been established theoretically by Adler and Baron (1979) and experimentally by Kamotani and Greber (1972, 1974). Kamotani and Greber (1972) examined the structure of heated and unheated circular jets in a crossflow and reported longitudinal and transverse velocity distributions, temperature and turbulence intensity profiles for a range of downstream locations. Adler and Baron predicted constant velocity distributions for different downstream locations with a range of jet to freestream velocity ratios and compared their results with Kamotani and Greber (1974). More recently, Sykes et al (1986) presented numerical calculations for the vorticity dynamics of a turbulent jet in a crossflow. As a general introduction to this particular flow model an up-to-date review of the aerodynamics of a jet in a crossflow has also been produced by Hancock (1987).

It must be appreciated that the above-cited literature is by no means a comprehensive review of circular jets in a crossflow. In fact, the references quoted are only a few significant examples from a vast wealth of theoretical and experimental investigations. The scope of the present study does not, however, demand a more comprehensive review as the investigation undertaken was intended as a demonstration of the digital imaging technique capabilities rather than an in-depth flow model study.
The jet in a crossflow configuration was established by directly utilising the smoke injection system outlined in section 4.6.2 with a suitable circular jet nozzle, the arrangement of which is shown in Figure 68. The jet issued from a copper nozzle, having an internal diameter of 19.05mm, the nozzle exit being mounted flush with the internal surface of the smoke tunnel roof and providing jet velocities up to approximately 5.0 m/s into still air. This velocity was reduced when issuing into a crossflow, due to the static pressure rise associated with the smoke tunnel facility (section 4.2). The velocity and turbulence intensity profiles associated with the jet were not quantified using traditional anemometry. A nominal jet to freestream velocity ratio of 4:1 was achieved using a freestream velocity of 1.0 m/s, representing a freestream Reynolds number of $1.3 \times 10^3$ and a jet Reynolds number of $5.1 \times 10^3$ (both based on jet nozzle diameter). A jet/freestream velocity ratio of 4:1 could be maintained for other freestream velocities by visualization of the jet, a constant mean pathline being established through adjustments to the jet exit velocity. Preliminary flow visualization studies were undertaken to reveal the shape characteristics of the jet in a crossflow profile. Illumination for these initial visualizations was provided by a vertical slit/exterior floodlighting combination as illustrated below.
This illumination facility provided a three-dimensional lighting arrangement, the flow being viewed as a 'slice' rather than a two-dimensional plane, with the CCD video camera located in the tunnel working section as shown above. The illuminated jet cross-section was located at approximately 20 jet diameters downstream from the jet exit centreline, the position of this location relative to the mean centreline path being shown below (reproduced from Adler and Baron (1979)).

Jet/Freestream Ratios

Plate 17 shows a sequence of four 'snap-shots' of the 'floodlight illuminated' jet profile. Whilst the overall shape characteristics of the jet are evident in these pictures, the three-dimensional nature of the illumination obscures the finer flow details, revealing little about the instantaneous, inner flow structure. In order to improve the illumination two-dimensionality, the rotating mirror scanner (section 4.6.3) was employed to produce a thin, vertical light sheet as illustrated below.
Whilst the video images recorded during the visualization experiments clearly revealed the counter-rotating vortices in the flow, single snap-shots of these structures were unable to convey a sense of this dominating flow structure motion. In addition to single snap-shots, the digital imaging hardware was used to produce a mean flow structure image by digitally averaging one hundred instantaneous flow images to produce a time-averaged picture. The real-time averaging procedure acquired sequential images at a rate of approximately two per second, a single summation representing approximately 45 seconds of flow visualization. Plate 17 also shows a digitally averaged mean flow image (top left) together with three instantaneous snap-shots of the turbulent jet structure. In comparison with the images obtained by flood illumination, these images represent a significant improvement in image detail. Plate 18 shows an edge-enhanced and pseudo-coloured zoomed display of one of the laser sheet illuminated snap-shots, together with a zoomed display of the digitally averaged flow structure. Plate 19 shows a filtered, pseudo-colour enhanced version, of the averaged jet structure together with a histogram equalisation image which has the effect of 'lumping' similar grey levels towards distinct levels. Plate 20 shows a pseudo-colour version of the equalised mean jet flow, together with its Sobel enhancement, illustrating the mean image intensity contours associated with the image.

Instantaneous images such as those in Plate 17 illustrate the truly intermittent nature of this particular flow model, these images differing significantly from the time-averaged structure shown in the same Plate. It is this highly intermittent nature which dictates that mean flow quantities cannot be simply achieved within a 'short' sampling period, meaningful averages requiring a statistically-orientated continuous analysis approach in order to satisfy accurate average requirements.

A quantitative analysis of the jet in a crossflow configuration was undertaken using the digital imaging
intermittency analysis previously described in section 5.3.1 of this dissertation. A composite intermittency map of the jet structure was achieved by illuminating the flow at a series of relative 'height' levels using the single laser beam as illustrated below.

A composite intermittency map, Figure 69, was achieved by transforming the resultant pixel intermittency functions into a two-dimensional map of iso-intermittency factors. The intermittency contours have been indicated from 0.0 to 1.0 at 0.1 intervals, the 0.0 intermittency contours indicating the absolute turbulent jet boundary encountered during the 100 second sampling period, the unity contour enveloping regions of continuous turbulence. This intermittency map would appear to agree very well with the overall shape and structure of the digitally averaged and pseudo-colour enhanced visualization images shown in Plates 18, 19 and 20.

A conservative estimate of the total experimental time required to produce the intermittency functions necessary to compute the intermittency map in Figure 69 may be calculated to be less than 30 minutes. Using more specialised digital imaging hardware (not available to this study) combined with laser sheet illumination (similar to that employed in this
section) it would seem reasonable to conclude that a similar whole-field intermittency map could be continuously acquired in real-time. Such a method would conceivably produce intermittency maps from 5,000 individual images in a maximum of 100 seconds. The experimental time required to produce an equivalent intermittency map using hot-wire anemometry, for instance, would possibly be of the order of hundreds of minutes, if not tens of hours, depending on the facilities available. The highly intermittent nature of turbulent jet configurations dictates that true mean value statistics may not be achieved within relatively short sampling periods and ideally, statistically-orientated sampling criterion should be satisfied before accepting quantitative data of any type.

Unfortunately, the smoke tunnel facility was not equipped with a suitable traversing mechanism to enable a comparative hot-wire intermittency analysis of the jet in a crossflow to be undertaken and, to-date, no directly comparable experimental published data has been discovered. As a source of tentative comparison, Sykes et al (1986) produced numerical calculations of a passive scalar distribution in a jet in a crossflow (jet velocity/freestream ratio of 8:1). Although not at the same downstream location, Figure 70 is a reproduction of their calculated scalar field at a downstream location of 6.5 jet diameters, with obvious similarities between this and the intermittency contour map of Figure 69.

The encouraging nature of the results presented in this section, combined with the proven quantitative analyses of the flat plate wake (Chapter 6) would appear to suggest that the digital imaging technique may indeed prove itself to be a most expedient, and possibly the only practicable means of establishing intermittency contour maps for this particular three-dimensional flow model. Although not examined in this study, previous results (section 6.3.5) would also suggest that perhaps mean fluctuating quantities may also simultaneously be resolved for this highly complex flow model. It is hoped, therefore, that this preliminary
investigation has substantiated these possible system attributes and that more detailed comparative studies may be undertaken in the future.

7.5 **Boundary Layer Modification by Passive Means**

The desire to minimise aerodynamic vehicle drag and a growing awareness with regard to energy economy have generated great interest in the development of techniques to reduce the viscous drag on aerodynamic bodies. Indeed, it is approximated that up to fifty percent of conventional aircraft drag is due, essentially, to skin friction from the turbulent boundary layer on the body. Relatively recent investigations of turbulent boundary layers by Head and Bandyopadhyay (1981) have highlighted the dominating presence of large scale structures such as hairpin and horse-shoe vortices. It is the existence of these structures and their contribution to a boundary layer's turbulence energy that has led to the possibility of turbulence control (and hence reduced skin friction, increased heat transfer or mixing) through various manipulation devices. Two approaches that have stimulated most interest in the realm of passive drag reduction have been the study of riblets and so-called large-eddy breakup (LEBU) devices. There would now appear to be little remaining doubt regarding the effectiveness of riblets to reduce skin friction drag and as recently reported by Wilkinson et al (1987), successful flight tests employing '3M vinyl riblet film' have been conducted by N.A.S.A. Langley on a Lear Jet. Another practical application of riblets was recently highlighted by the 1987 U.S. America's Cup challenger, Stars & Stripes, which also employed the 3M riblet product over the yacht's submerged hull and, of course, achieved a significant victory. Outstanding problems regarding the successful application of riblets to aircraft were quoted by Wilkinson et al as being questions concerning riblet porosity and particle adhesion.
Large-eddy breakup devices in the form of 'ribbons' or thin plates have also been found to produce net drag reductions of the order of five to fifteen percent (although large variations in results have caused concern about the large-scale applicability of these devices). An account of the historical development of large-eddy breakup devices (LEBUs) schemes was reported by Mumford and Savill (1984). Bertelrud and Watson (1987) reviewed flight tests undertaken at high subsonic Mach numbers (Mach 0.7) with LEBU ribbons constructed from spring steel. Aerofoil-shaped LEBUs, required for greater structural rigidity at high speeds, have been shown by Anders and Watson (1985) to produce up to seven percent net-drag reductions.

A wide range of wind tunnel tests undertaken in recent years has indicated certain optimum LEBU design parameters:

\[
\text{chord/} \delta_{0.99} > 1.0; \quad h/\delta_{0.99} = 0.6 - 0.8; \quad \text{gap/} \delta_{0.99} = 5 - 10.
\]

where, \(\delta_{0.99}\) is the boundary layer depth, defined as the 99.0 percent mean velocity location.

Possible explanations as to why LEBU devices achieve skin friction reduction include:

(a) blocking effects of an embedded, impervious surface,
(b) momentum deficit of the device wake,
(c) turbulence distortion,
(d) vortex 'unwinding',
(e) downstream influence of LEBU shed vortices, and
(f) macro-movement of momentum away from surface due to device circulation.

All of the above-suggested mechanisms may contribute towards the potential effectiveness of LEBU devices, but the dominant mechanism(s) remain, as yet, uncertain. In addition to their applications as drag reducing elements, LEBUs may be applied to noise-reduction problems, and offer the potential of enhanced relaminarisation techniques to further reduce drag effects and increase aircraft control. Visualization of the flow structures associated with LEBUs
has been limited to rather inconclusive smoke-wire studies, Corke et al (1982) and Heffner et al (1983), a more informative smoke injection investigation by Mumford and Savill (1984) also undertaking hot-wire and local skin friction drag measurements.

Mumford and Savill's (1984) flow visualization studies were conducted in a 12.0m * 0.91m * 0.91m low-speed suction tunnel previously used by Head and Bandyopadhyay (1981), who described the illumination and tunnel facilities in detail. The boundary layer was visualized by injecting smoke either through a row of holes just behind a roughness trip or, more smoothly, through a gauze-covered slot some distance downstream to observe near-wall disturbances. The smoke tunnel was operated over freestream velocities ranging from 1.0 to 2.4 m/s which, at the measuring station, produced a Reynolds number based on momentum thickness, $Re_{\theta}$, of between 700 and 1600. The boundary layer was illuminated using either two 1000 W tungsten iodide lamps or by a laser light sheet produced by a 5 W argon-ion laser. Visual recordings of the flow structures were made by still photography or a 16mm ciné camera operating at 64 frames per second. Mumford and Savill presented idealised representations of the flow structure modifications caused by LEBU devices of various geometries based on their visual and photographic records. Combined with their quantitative velocity and drag measurements, these visualization experiments proved to be an invaluable information source from which complex flow interactions and associated turbulence manipulation contributions were postulated.

The aim of this investigation was to visualize typical turbulent boundary layer flow structures and observe how the presence of LEBUs affected their development. The digital imaging contribution to this study was purely qualitative, limited quantitative flow details being acquired via hot-wire anemometry. Before examining the experimental details, it would seem reasonable to briefly examine the more recent investigations of unmanipulated turbulent boundary layers
which have involved flow visualization. Falco (1980), for instance, combined simultaneous hot-wire anemometry with flow visualization in order to condition his anemometer signals to the visualized turbulent structures. Visual data from two mutually orthogonal illuminated planes was simultaneously acquired, revealing the strong three-dimensional nature of even the large boundary layer structures.

Head and Bandyopadhyay (1981) used a combination of flow visualization and hot-wire anemometry to study turbulent boundary layers over a large range of Reynolds number. At high Reynolds numbers (Re > 2000, say) the layer consisted largely of elongated hairpin vortices or vortex pairs, originating in the wall region and extending through a large part of the boundary layer thickness. The vortices were found to be predominantly inclined to the wall at a characteristic angle in the region of 40 to 50 degrees. At low Reynolds numbers (Re < 800, say) these hairpin vortices were very much less elongated and were better described as horseshoe vortices or vortex loops.

The boundary layer for this digital imaging investigation was produced on a nominally two-dimensional flat plate model, Figure 71. Constructed from plyboard, the model spanned the 0.75m height of the smoke tunnel and was aligned parallel to the freestream flow direction, along the tunnel centreline. The model depth was 0.75 inches (19.05mm) which represented an area blockage ratio of 3.1 percent. The boundary layer was 'tripped' by a 1.0mm diameter wire secured to the plate surface, located 10.0mm from its leading edge and was visualized by smoke injection directly into the layer from 1.0mm holes spread over a 20.0mm extent of the central span. These holes were located 40.0mm from the model's leading edge and extended over a 10.0mm width. Smoke was fed to the holes via a recessed smoke-tube allowing the surface of the plate to have a perfectly smooth finish. Figure 72 shows the details of the LEBUs which, being constructed from brass, were filed to produce sharp
leading and trailing edges. The height of the LEBUs above the flat plate surface was adjustable between 10.0 and 25.0mm, in 5.0mm intervals. The LEBUs' chord/\( \delta_{0.99} \) ratio of 0.71 was less than the previously quoted optimum (> 1.0) and the gap/\( \delta_{0.99} \) ratio of 3.9 was far from the widely accepted optimum range of 5 to 10 (9 according to Savill (1986)).

In order to achieve reasonably blur-free flow visualization snap-shots, a trial and error procedure identified a maximum freestream velocity for the boundary layer experiments of 1.0 m/s, which was maintained for the following series of manipulated boundary layer investigations. A combination of ad hoc flow visualization and coarse hot-wire traverses also allowed locations for the positioning of the LEBUs to be determined and a suitable measuring station further downstream to be identified. The mean velocity profile of the unmanipulated turbulent boundary layer at the chosen LEBU station (315mm from the leading edge, \( R_{ex} = 2.11 \times 10^4 \), \( R_{e\theta} = 205 \)) is shown in Figure 73, whilst the mean velocity profile at the measuring station (620mm from the leading edge, \( R_{ex} = 4.16 \times 10^4 \), \( R_{e\theta} = 262 \)) is shown in Figure 74. Calculation of the boundary layer parameters at these two stations revealed an overall mean velocity inverse power-law of the order of 4.8, the boundary layer height (\( \delta_{0.99} \)) at the LEBU station being 28.0mm, and 36.0mm at the measuring station. The boundary layer under study was obviously far from fully turbulent (\( R_{e\theta} > 5000 \)) and should be regarded as a preliminary test model for visualization experiments, not as a fundamental, detailed investigation. Quantitative analysis of the mean velocity profile at the downstream measurement station was conducted with the tandem LEBU arrangement at 10.0, 15.0, 20.0 and 25.0mm heights above the plate surface, representing dimensionless heights (\( h/\delta_{0.99} \)) of 0.36, 0.54, 0.71 and 0.89, respectively. The mean velocity and turbulence intensity profiles for the above LEBU configurations are shown in Figures 75a to d, the various boundary layer parameters being compared with the 'No LEBU' case in Table 5.
<table>
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<th>LEBU Height h/δ₀&lt;sub&gt;0.99&lt;/sub&gt;</th>
<th>Displ. Thickness δ*(mm)</th>
<th>Mom. Thickness θ (mm)</th>
<th>B/L Height δ₀&lt;sub&gt;0.99&lt;/sub&gt;(mm)</th>
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Table 5. Manipulated Boundary Layer Parameters

It is evident from the boundary layer velocity profiles (Figures 75a to d) and the momentum thickness values presented in Table 5, that the manipulation of the boundary layer via the various tandem LEBU arrangements was unsuccessful at reducing the overall skin friction drag. This finding does not appear to support the assumption that boundary layer manipulation through the use of LEBUs is capable of reducing skin friction drag, but considering the crude nature of the LEBU device employed for this study, such results were not totally unexpected, nett drag reductions being impossible because of excessive LEBU device form drag. Mumford and Savill (1984) experienced a similar result with LEBU plate thicknesses of 1.2 and 0.56mm, but predicted that for a device thickness of 0.10mm, form drag would become negligible. Appreciating that the LEBU devices were not of optimum design, smoke flow visualization experiments were conducted to assess the qualitative boundary layer effects of the LEBUs at the various non-dimensional heights previously detailed for the quantitative analyses.

The flow visualization experiments were conducted under identical flow conditions to those previously outlined for the hot-wire velocity profile studies. The flows were visualized through a laser/vibrating mirror combination (section 4.6.5) which produced a two-dimensional laser light sheet as illustrated overleaf.
Alternative lighting configurations using the rotating mirror scanner, with the light plane normal to the flat plate, were attempted but were unsuccessful because of the limited scanning plane and blockage effects due to the experiment's confined nature. The final arrangement of the laser scanner, although adequate for the present study, was not ideal as the boundary layer and light sheets were growing laterally in opposite directions. With a more powerful laser source this may not have been a great problem but with the 5 mW Helium-Neon laser, illumination levels within the laser sheet could only clearly be detected in the narrower regions of the sheet. The final location of the laser scanner was, therefore, interactively adjusted to ensure maximum illumination at the viewing region of interest. The sketch below illustrates this and also indicates the visualized model flow region.
The object of the visualization experiments was to investigate the flow structures associated with the boundary layer immediately downstream of the second LEBU in the tandem arrangement. Unfortunately, it was not possible to observe the flow over any part of the LEBU devices as the high intensity reflections caused by the laser sheet impinging on the LEBUs were too intense to enable digitised video images to be acquired. Flow structure snap-shots were achieved by synchronising a single laser sweep across the flow with a single field exposure on the CCD video camera (integration period of 8 mS). Whilst this technique produces a nominally blur-free image, some image distortion may occur as illustrated below.

In a boundary layer flow, the differential velocity across the flow height, indicates that a differential distortion of a scanned image may also be expected. For this particular study, an 8 mS field-scan period was synchronised with the laser scanner to produce images with a maximum distortion factor (defined as differential movement/field movement) of between 1.0 and 2.5 percent. This degree of image distortion is negligible, but was only achievable because of the low downstream velocity (< 1.0 m/s) of the boundary layer flow structures. At higher freestream velocities, higher scanning and framing rates would be necessary unless the video camera could be traversed at the same velocity as the flow structures (i.e. zero relative velocity). In the present investigation, there were no synchronising facilities
between the laser scanner and video camera, dictating that full-field illuminated and scanned images were seldom simultaneously achieved, the majority of digitised images being only partially illuminated or partially illuminated twice near the scanner plane 'edges'. As a point of interest it may be observed that systems only offering a slow sampling rate (say, 50 Hz) can be used to produce excellent 'double exposures' of a flow using a suitable scanning frequency, allowing near-instantaneous movements of flow structures to be closely observed within each acquired image. In all instances, the flow direction for the visualized images shown in the boundary layer Plates is from left to right.

Plate 21 shows a typical selection of four images (not sequential) characterising the boundary layer flow without LEBUs together with a zoomed display of one of the four images. Plate 22 shows a similar display format for LEBUs at a non-dimensional height of 0.36, Plates 23, 24 and 25 showing similar displays for non-dimensional LEBU heights of 0.54, 0.71 and 0.89, respectively. Plates 21 and 22 for the 'No LEBU' and 0.36 non-dimensional LEBU height cases appear to illustrate many of the typical and globally accepted turbulent boundary layer characteristic structures, including inclined horseshoe vortices, turbulent bursts and 'mushrooms'. Plates 23, 24 and 25 appear to illustrate the disruptive nature of LEBUs with respect to these structures, the inclined vortices being 'sliced', the LEBU wake shear layers isolating the 'upper' and 'lower' regions of the flow and a general retardation of the flow regions occurring between the LEBUs and the flat plate surface.

In addition to these instantaneous structure observations, it was also possible to accumulate an average flow structure picture through digitally averaging one hundred sequential image fields. (The rate of acquisition in this mode was approximately one or two images per second and not fifty fields per second as achieved in other sequential acquisition applications). Plate 26 shows the averaged flow
structure pictures with the non-dimensional LEBU heights being, from top left to bottom right, 0.89, 0.71, 0.54 and 0.36, respectively, together with a zoomed display of the 0.89 case. These images highlight quite distinctly the wake region of the LEBU arrangements (illumination shadowing effects are not present) and offer, perhaps, a possible means of observing the effect of LEBUs on the mean turbulent boundary layer structures with respect to overall growth rates with, for instance, downstream location. Unfortunately, because the laser scanner was not synchronised with the video sensor, it was not possible to obtain sequential records of boundary layer movements (as previously illustrated in other sections) and such facilities should obviously be incorporated into future studies of this nature.

Whilst the present investigation has been relatively limited and somewhat crude with respect to model configuration, illumination facilities and LEBU design, it has nevertheless demonstrated that flow visualization may offer an expedient means of studying boundary layer manipulation. In particular, the digital image averaging approach would appear to offer a means by which the effects of different model configurations may be quickly assessed with respect to the overall boundary layer development. Further experimentation along these lines would, however, benefit enormously from an improved illumination facility, more sensitive, higher rate solid state or cinematographical devices and more involved design and construction techniques for the model equipment (in particular the LEBU devices).

Further quantitative measurements, obtained via Preston tubes, have recently been obtained by my colleague Dr E Savory, the results of which are to be presented in July 1989, see 'Publications Associated With This Thesis'. 
7.6 Dynamic Stall on an Aerofoil

The flow characteristics of a pitching aerofoil have attracted much attention in recent years. The advent of new aircraft capable of pitching at high angular rates has, for instance, increased the desire for knowledge concerning the phenomenon of dynamic stall. The constant rate pitching of an aerofoil has also been found to produce lift coefficients of more than double the maximum static lift coefficient. The reproducibility of initial lift data and the character of the drag and moment curves seems to suggest that the manageable behaviour of a constantly pitching aerofoil may be suitable for aircraft stability-and-control purposes. Ericsson and Reding (1971) reviewed the experimental data relevant to dynamic stall and more recently, the lift-curve characteristics and pitch location effects have been examined by Jumper et al (1986, 1987), respectively.

The flow characteristics associated with dynamic stall have been visualized by smoke-wire in air by Walker et al (1985), who also performed near-surface hot-wire measurements. Their visualization experiments revealed that a leading edge vortex was formed and as the angle of attack of the aerofoil increased, the vortex continued to grow and move away from the aerofoil surface. It was suggested that the maximum lift occurred when the vortex was well developed yet still relatively close to the surface. The hot-wire data was rationalised using flow visualization results and reportedly indicated reverse flow velocities near the aerofoil surface of 1.0 to 2.1 times the freestream velocity. These maximum reverse flow velocities occurred for any given angle of attack directly under the centre of the 'dynamic vortex'. Gad-el-Hak (1986) reported a water-based dye-layer technique for visualizing the unsteady flow around three-dimensional lifting surfaces undergoing harmonic pitching moment. More detailed visualizations using the same technique were also presented by Gad-el-Hak and Ho (1986).
Mankau (1982) successfully demonstrated that very similar flow structures to those previously described in connection with dynamic stall are also present in the flow over an oscillating cantilever roof. Pressure measurements and flow visualization results were achieved with the roof oscillating through a total angle of 30 degrees, its mean position being horizontal. The pressure coefficients obtained were compared between fixed and oscillating cases, and were found to reach a maximum of approximately three times those of the fixed case when oscillating. Mankau's flow visualization results indicated the growth and shedding of a leading edge vortex in a very similar manner to that reported for dynamic stall experiments.

The present study has visualized a dynamic stall flow configuration using smoke in the smoke tunnel facility, and was undertaken in conjunction with a quantitative lift and drag strain-gauge analysis using the same model in the larger boundary layer tunnel. These strain-gauge experiments were undertaken by colleagues of the Author, namely, Drs Toy and Savory. The visualization results are, at present, of a purely qualitative nature but it would appear from the reviewed literature that the complex nature of this phenomenon demands the use of such an approach in order to begin to formulate a suitable flow model scenario. It would seem reasonable to propose that future experimental investigations using standard velocity or pressure sensing devices should be accompanied by simultaneous visualizations of the flow structure. Once again, it should be noted that the results presented in this sub-section are only indicative of possible experimental techniques and should not be regarded as definitive flow studies.

The dynamic stall of a pitching aerofoil was investigated using a normal and 30 degree swept back constant-chord wing model. The aerofoil sections were similar to the European Airbus (A300 Series) having a chord length of 0.19m and a normal span of 0.61m, resulting in an aspect ratio of 3.2:1. The overall model dimensions are illustrated overleaf.
At pitching incidences from -5 to +35 degrees, the aerofoil had a smoke tunnel variable blockage ratio (depending on incidence) from 1.8 to 7.0 percent, respectively. In order to facilitate adequate flow snap-shots, the freestream velocity of the smoke tunnel was restricted to 4.0 m/s, giving an aerofoil Reynolds number (Re_c) based on chord length of 0.51 * 10^5. Pitch oscillation of the wings was achieved via a hand-operated rotary traversing stage (previously described in section 4.2) which, due to the smoke tunnel's 'increased' working section static pressure, rotated under near air-bearing conditions. Using this mechanism it was possible to pitch the wing models from an attitude of -5 to +35 degrees with a variable pitching time between 0.25 and 0.5 seconds. Estimates of pitch rates were obtained by stopwatch observations (the dial of the stopwatch being visible in the video camera field-of-view), the average pitching duration being 0.3 seconds (-5 to +35 degrees). The non-dimensional pitch rate \( \dot{\alpha}_N \) is defined as:

\[
\dot{\alpha}_N = 0.5 \frac{c \, \dot{\alpha}}{U_0}
\]

where, \( c \) is the chord of the aerofoil in m, \( \dot{\alpha} \) is the pitching rate in rads/second, and \( U_0 \) is the freestream velocity in m/s.
The non-dimensional pitching rate, $\dot{\alpha}_N$, was approximately 0.055 for all of the visualization experiments reported in this section. The contaminant introduction system for this study consisted of injecting smoke through a horizontal slit in a free-hanging smoke-tube as illustrated below:

The smoke-tube section labelled 'A' was interchangeable to allow vertical re-positioning of the smoke slit, although all of the reported visualizations were conducted with the slit at approximately the model mid-span, 300mm from the tunnel roof. Illumination was achieved by external 300 Watt floodlighting, care being taken to mask regions of the model other than those required (to avoid stray reflections).

Preliminary static incidence flows were visualized for the normal wing model, the aerofoil being stalled at an incidence of +15 degrees, the flow still being attached at +10 degrees incidence. This indicated stall range was in agreement with the generally accepted stall angle for this model of approximately +12 degrees.

The dynamic pitching model flow is captured in Plate 27, the model pitching from +15 to +35 degrees before reversing with negative pitch from +35 to +15 degrees. The so-called dynamic vortex formation and initial shedding stages are clearly evident in this Plate during the positive pitch, negative pitch causing the breakdown of this formation. Plate 28 shows an original zoomed display image of a typical
dynamic vortex formation together with a Sobel-operated image, highlighting the detail of the light gradients.

A comparison of the static and dynamic aerofoil pitching experiments revealed that in the dynamic case, the flow at +15 degrees is still attached to the wing and remains so throughout the vortex formation until approximately +30 degrees, where the vortex breaks away from the aerofoil surface. In addition, the visualizations of the dynamic vortex formation demonstrated a three-dimensional aspect of the growth process, the vortex moving towards the aerofoil tip before shedding in the direction of the freestream flow. This process is evident in the visualized images as a 'corkscrew' appearance to the dynamic vortex, this movement towards the camera causing the vortex to appear out of focus.

Static incidence flows for the swept wing model at the mid-span location indicated that local static stall was observed to occur at between 12.5 to 15.0 degrees incidence. Compared to the normal model case the swept wing displayed a weaker dynamic vortex formation with no apparent collapsing vortex at maximum incidence as had been observed with the normal wing, Plate 29 (the camera viewing angle being normal to the model span). Once again, the swept wing dynamic vortex migrated towards the wing tip during pitching, causing an out of focus effect in the video image before shedding in the freestream direction.

Savory and Toy (1987, 1988) presented some experimental results for dynamic stall of the normal and swept wing models, respectively. Lift and drag data were obtained from the wing models through strain-gauge measurements in the boundary layer tunnel at a freestream velocity of 10.0 m/s, corresponding to a chord Reynolds number of $1.34 \times 10^5$. The non-dimensional pitching rate was varied between 0.005 and 0.032 with an investigation of aspect ratio also being undertaken through the addition of 0.15m (normal dimension) aerofoil extension sections to the test models.
A typical lift coefficient relationship with angle of incidence at varying non-dimensional pitch rates for the short swept wing is shown below.

Interpretation of the lift data for the above and similar experiments allowed the variation of dynamic stall angle with pitching rate to be established as shown below.
These and similar experimental results on the normal and swept wing models may be more simply understood when reviewed in context with the flow visualization studies reported in this section. In addition to this simplistic yet invaluable use of the flow visualization results, it would seem highly desirable at a future date, perhaps, to incorporate both quantitative lift, drag and surface pressure measurements with simultaneous flow visualizations of the dynamic vortex formation. Digital image analysis of these visualizations could also then be used to quantify aspects of the vortex, such as centre location (perhaps in 3-dimensions) with respect to incidence angle, growth rate and mean formation strength. Investigations of this type could conceivably allow the dynamic vortex motion to be visually tracked in three-dimensions, with intimate knowledge then being applicable to more established quantitative techniques. This type of experimental approach would, of course, also be suitable in many other instances of unsteady flow and not limited solely to dynamic stall investigations.

7.7 Vapour-Screen Visualization

The work reported in this sub-section has been undertaken to improve the visual detail of flow visualization images achieved within the 8-foot high-speed wind tunnel at the Royal Aerospace Establishment (formerly the Royal Aircraft Establishment), Bedford. The visualization technique used for this study involved a vapour-screen technique (outlined later) combined with laser sheet illumination, the test models being wall-mounted half-models (precise details not necessary). The resultant visualizations reveal shock waves which, for each chosen model attitude and test condition, remain stationary with respect to time. A detailed description of the experimental apparatus involved in this study is not included in this sub-section, the only important details necessary to the following discussions
The vapour-screen method of flow visualization in supersonic wind tunnels was first employed by Allen and Perkins (1951), the principle of operation being simply to run the tunnel with moist air. As the air expands through the supersonic nozzle into the working section it cools, allowing the moisture to condense out and form a fog. This fog is illuminated by a narrow beam of light (laser) perpendicular to the model axis. Any disturbance in the crossflow plane, such as that caused by a model at incidence disturbs the uniform distribution of fog particles within the vapour-screen plane (and hence the amount of light scattered by the fog). In particular, wakes, vortices and shock waves appear as dark regions within the illuminated screen. On passing through a shock wave air undergoes a very rapid deceleration which fog particles cannot follow (due to their much greater inertia). A relative velocity therefore exists between the air and fog particles, which will, however, be quickly reduced by the action of viscosity and, a short distance after passing through the shock, steady-state conditions are re-established (fog density again proportional to the local air density). At a shock wave location there is a sudden increase in density and the screen appears lighter due to the greater concentration of fog particles. The position of
a shock therefore corresponds with boundaries between a darker and lighter region, an idea of the shock strength being given by the change in shade between two such regions.

From a photographic viewpoint, the optimum fog density is a compromise between two conflicting requirements. If the fog is too thin, a long exposure time is needed and there is a risk of light reflections obscuring the low-contrast vapour-screen image or camera vibrations blurring the entire picture. On the other hand, if the fog is too dense, there is excessive light scattering between the vapour-screen plane and the camera lens, resulting in poor, indistinct pictures with little detail (a similar problem to that previously reported in previous sections with respect to the smoke flow visualization technique).

The vapour-screen technique affords a simple and practical method of flow visualization at supersonic speeds, and, with some limitations, may even be employed at Mach numbers as low as 0.85. It is capable of providing useful information about flows over and behind wings and bodies, such details as vortices, vortex sheets, lines of low separation or reattachment and shock waves being rendered visible. A comprehensive introduction into the vapour-screen method of flow visualization was produced by McGregor (1961).

The previously shown illumination and viewing arrangement illustrates clearly that the so-called 'pod' camera is located in a suitable position to give undistorted, visualized images (viewing at right angles to the illumination source). The discussion in section 4.8.2 has, however, indicated that from a scattered light viewpoint, this viewing angle is also the worst possible location for yielding 'good' image intensities. A camera external to the working section observes back-scattered light which should yield better image intensities, but with a spatially distorted image. It would, perhaps, be possible to digitally correct this distorted image to produce a normal viewing angle projection. Such an undertaking may, however, be
extremely complicated and time-consuming (without specialist hardware) and an alternative solution to this problem was sought through the application of real-time image enhancement techniques to the undistorted pod camera images. The imaging facilities described in section 3.4 and used throughout the preceding imaging applications were not capable of real-time image processing but could be programmed to perform software-based image processing (previously outlined in section 7.2 of this chapter). In order to increase the processing capabilities of the digital imaging system it was necessary to add specialised imaging modules to the existing IP-512 system, these being:

1. ALU-512 Arithmetic Logic Unit,
2. HF-512 Histogram and Feature Extraction, and
3. FB-512 Frame Buffers.

Note: Unlike the imaging system used for the quantitative study (Chapters 4, 5, 6) the frame buffers used in the above configuration were limited to 512 * 512 addressing, the processing functions operating exclusively on 512 * 256 resolution fields.
The ALU-512 board is a high-speed, pipelined processor that supports real-time, full-field arithmetic and logical image processing functions, performing 10 million operations per second. The functions supported include unsigned or two's complement 8-bit multiplication, 16-bit addition, subtraction, XOR, OR, AND plus arithmetic or logical shifts. The HF-512 board computes digital image histograms and extracts pre-programmed intensity features in real-time, allowing on-line contrast enhancements to be performed through subsequent histogram manipulations. The two additional FB-512 boards were necessary to store the 16-bit resultant images from the ALU-512 board computations (only 8-bits (MSB or LSB) of which may be displayed).

The real-time imaging system was used to analyse vapour-screen visualizations which had been recorded via a U-matic video tape recorder at R.A.E. (Bedford). Precise details of the experiments conducted are not required for this discussion, although it must be emphasized that the quality of the video signals replayed in this manner were not perfect, the original signals being degraded considerably through use of a VTR. In addition, it should be further appreciated that the operating environment to which the video cameras were subjected within the high-speed tunnel was not ideal.

Unfortunately, the continuous real-time digitisation of a 'raw', replayed video tape signal is difficult, the analogue signal produced by a VTR being imperfect with respect to its field and line synchronisation ('sync. pulses'). Individual field digitisations may be achieved without great difficulty from any reasonably 'good' quality video source, but real-time image processing requires continuously 'perfect'

Note: The above enhanced system would not offer any improved system performance with regard to the quantitative imaging technique previously described in this thesis, although the feature extraction capability of the HF-512 module may conceivably be utilised for full-field spatial correlations.
signals, all system errors being cumulated with respect to the output image. The vapour-screen visualizations were only available on U-matic video tapes which made 'raw signal' real-time imaging almost impossible. Signal rectification and stabilisation was, however, achieved using a Digital Frame Store device (the modern equivalent of a Time Base Corrector (TBC)), to process the video signal before entering the digitising board (AP-512).

The real-time image processing software was written using Fortran 77 as the Input/Output language (including the user interface) with imaging board-level control sequences being written in low-level machine-code (Macro II). The complete programme suite allowed total system control from a single key-stroke command environment, imaging routine variables being prompted for, if required. All run-time initialisation demands, such as allocation of device port globals, etc., were implemented upon LOGIN to the appropriate system directory, from which a user was then unable to perform any system functions other than those executed under the control of the image processing suite. The block diagram overleaf illustrates the options available to the user from within this imaging suite.

Full implementation of the enhanced digital imaging system enabled real-time image processing functions to be performed on incoming video signals. The term 'real-time' in this context is somewhat imprecise as the actual image output rate may vary from 50 down to 2 or 3 processed fields per second. Fundamentally, logical function transformations may be performed once per field period (via the ALU-512), with an \( N \times M \) convolution requiring \( N \times M \) field times. The \( 3 \times 3 \) transformations outlined in section 7.2 (high-pass, low-pass filters plus one-dimensional Sobel operations (horizontal or vertical masks)) may be performed in real-time, yielding approximately 5 processed images per second, whilst a real-time, two-dimensional Sobel operation would have an output rate of only 2.5 images per second. A weighted average algorithm, on the other hand, multiplies a stored image by
some constant, adds it to an incoming image, scales the result to 8-bits, and stores the quotient back to the original frame buffer. This operation repeats, giving the effect of blurred motion (if the image is not stationary) whilst improving the picture's signal-to-noise ratio, the output image rate being 50 fields per second (real real-time!).

Real-Time Imaging Software Overview

Although not indicated in the above overview, each of the above modules may be selected directly from within any other module, the 'Main Menu' being common to all.
The programming requirements necessary to implement all of these convolutions and operations are relatively uncomplicated, the most critical aspect of their operation being timing constraints and 'spin compensation' allowances which reflect the pipelined nature of the image computation functions (output image delayed by 11 pixels (512 resolution) relative to original). It should be appreciated that 'absolute' real-time image processing may always be achieved by using dedicated hardware facilities or parallel processors, the output rate for all processing functions being maintained at 50 fields per second, but demanding a great deal of expense and limited flexibility.

The visual quality of the poorly illuminated vapour-screen visualizations could be improved through weighted image averaging (to improve the image signal-to-noise ratio) combined with contrast enhancement through histogram stretching or equalisation procedures. The resultant images could then be thresholded, filtered and Sobel operated to reveal precise shock locations, with pseudo-colouring perhaps aiding the final display quality. Plate 30 shows an original illuminated sheet visualization plus an enhanced image processed in this manner, the results proving to be somewhat disappointing. The quality of the results is, however, highly dependent on the original image intensities, which may be seen to provide negligible contrast between the shock and background vapour-screen. Low-pass filtering to remove image noise should be avoided for this application as this would degrade the shock details.

Previous experience had indicated that much improved illumination levels could be produced by restricting the laser scanning region to a narrow 'strip' rather than a full-field sweep. Under such circumstances the shock detail could be relatively improved providing that it was possible to compute a complete full-scan image from a sequence of narrow region illuminations as schematically illustrated overleaf.
An initial attempt to implement an image addition function of this nature was undertaken using software-based routines. The resultant programme was capable of continuously summing full-field images (using either a rolling mean or highest encountered pixel intensity approach) with a processing rate of approximately one image per second. This software was further enhanced to enable a variable line dimension (pre-set by the operator) and a simple line finding capability in order to indentify relevant image areas and reduce the overall image transfer requirement. The streamlined version of this software programme operated on approximately three to four fields per second, depending on the inclination of the illumination region within the field-of-view. In general, the operating procedure required a tape sequence to be repeatedly played in order to gradually build up a composite image, each tape pass allowing different illuminated locations to be processed. The quality of the resultant images was highly dependent on the number of fields examined, Plate 31 illustrating the results achieved using approximately 1000 image summations, a Sobel-operated enhancement also being shown. Due to the lack of complete image information, the Sobel image in Plate 31 is complicated by illumination sweep effects (horizontal lines). The complete image was cumulated using approximately ten tape passes, requiring over twenty minutes of operator control.
Using the real-time imaging system it was possible to perform real-time image summations as an on-line function (logical OR operations which tend the image pixel intensities to discrete bit level values), with the option of high-pass filtering, thresholding and Sobel operations, combined with pseudo-coloured displays, to further enhance the resultant image detail, Plate 32. The very distinct outline of the shock wave in this Plate not only provides a good visual indication of the shock location but also provides the foundation for an automated, quantitative shock location recording procedure. Using the Sobel-operated image, it would, for instance, be possible to directly output the shock wave location as a digital plot, or store its location details (coordinates) to disk for future analysis by appropriate graphics or 3-D evaluation routines. It should, however, be noted that the real-time continuous OR approach to image summation provides no information with regard to the change of light intensity across the shock location (the original pixel intensities being lost within the summation process). Where such information is particularly desired, the previously outlined software-based compilation programme would offer a true image intensity comparison (the images being averaged with respect to time). It may therefore be observed that complete shock wave information may be quantitatively achieved using a combination of both hardware and software-based processing algorithms, the results in both cases being significantly improved over full-field illumination enhancements (itself a worthwhile improvement compared to the original 'raw' images).

Future modifications to this particular imaging application could involve incorporating the image enhancement suite as an on-line facility within the testing facility at R.A.E. Bedford. The quality of the results would immediately be improved due to the avoidance of a VTR as an input source, although some form of secondary recording equipment would always be recommended. In such a case, the interactive capability offered by an on-line system could conceivably
lead to appropriate adjustments of the experimental conditions (such as the illumination levels and sweep characteristics), the resultant effect being a further possible improvement in overall system performance.

7.8 Shear Stress Sensitive Liquid Crystals

The work presented in this sub-section has been inspired by the ever-increasing interest being shown in the exploitation of shear sensitive liquid crystals to visually indicate global shear stress values on aerodynamic models. The degree of interest recently generated in this topic was clearly demonstrated by an attendance of over sixty UK aeronauticalists at a workshop on "The use of liquid crystals in flight and in the wind tunnel", held at the Royal Aerospace Establishment Farnborough, February 1988. A great deal of this interest has undoubtedly been generated through the experimental investigations currently being undertaken by Messrs. Gaudet and Gell, based at the R.A.E. Bedford, who have employed a range of liquid crystals on various models at high subsonic speeds within wind tunnel environments. The Author's interest with regard to the quantification of shear stress sensitive liquid crystals has been primarily motivated through the efforts of these latter two investigators.

The quantification of surface shear stresses (and associated skin friction) on aerodynamic models is important for the study of transition effects, drag prediction, overall vehicle performance and may assist in understanding local boundary layer behaviour. Settles (1986b) reviewed the numerous techniques which have been developed to measure surface shear stresses, both for wind tunnel and in-flight environments. Such techniques include the floating element drag balance, heated film or wire gauges and Preston tube, to mention only a few that have been successfully applied to many aerodynamic applications. Whilst not wishing to discuss the many limitations and assumptions necessary to operate
these devices, it should be noted that their common experimental attribute is that they quantify shear stress values either as point or mean local area measurements. A thorough investigation of a model's entire surface area using such devices is laborious, experimentally complicated, fundamentally inefficient, time-consuming and expensive. It is not surprising, therefore, that detailed experiments of this nature are rarely undertaken, nor that the possibility of a global shear stress indicator technique has attracted so much interest. As an example of the visual results produced by liquid crystal visualization, Plate 33 shows the degree of global detail visible on a stub wing model at approximately Mach 0.8 (R.A.E. Farnborough, 2.0 * 1.5 foot transonic tunnel).

Originally discovered in 1888, liquid crystals possess the physical properties of both their liquid- and solid-phase and in exhibiting the properties of solid crystals, selectively scatter a range of light wavelengths. Whilst most historical interest has rested on their temperature response characteristics and use in electronic (LCD) displays, other uses have included non-destructive material flaw testing, electronic circuit integrity tests and medical applications. Within the last two decades, liquid crystals have also been used in aerodynamic applications (mostly using their temperature response characteristics), for supersonic and hypersonic applications in wind tunnels, reported by Klein (1968), Schoeler (1978), and Schoeler and Banerji (1983). Liquid crystals possess a helical molecular structure with the helix pitch, p, having a length similar to visible light wavelengths.

\[
0.5 \times \text{Pitch}
\]
The pitch length of the liquid crystal helix is normally altered by changes in shear stress and temperature, although phenomena such as ferro-magnetism and some chemical vapours may also have an influence. Through this variable molecular helix pitch length, liquid crystals selectively reflect discrete colour wavelengths in a response to these influences. Since the crystal's basic chemical structure is not affected by such changes, colour variations are reversible and repeatable, with response times of less than 20 mS. The particular reflected colour observed generally depends on the local shear stress and temperature to which the liquid crystal is subjected, whilst the intensity of the colours depends on the incident light energy and its incidence angle. The two classes of liquid crystal that possess this requisite helical structure are called chiral nematic and cholesteric, other liquid crystals being nematic and smectic.

In temperature sensitive applications requiring minimum shear stress response, liquid crystal compounds may be encapsulated. In highly compressible flows, encapsulated compounds provide transition information because of the large temperature variations which occur between laminar and highly turbulent boundary layers. For subsonic visualization of transition, separation and shock locations, liquid crystals must respond primarily to shear stress with minimum temperature sensitivity. The more recent successes in transition visualization under in-flight conditions have been due to advances in liquid crystal technology, formulations now being available for a wide range of temperature bandwidths. It is now possible to formulate crystals to change colour across the entire visible spectrum (violet to red) over temperature bandwidths up to 32 degrees Centigrade (90 degrees Fahrenheit). Optimum visual and photographic results have generally been obtained using liquid crystal coatings on a matt black surface, the coatings being applied by brush or spray. Application methods normally require a thinning agent to be used, popular (not with ecologists) solvents being trichloro- or
trifluroethane, the liquid crystals being diluted in a ratio of 1:8 to 1:16, with a minimum crystal coating depth of 8 to 10 microns. Physical parameters that would appear to affect the use of a liquid crystal compound on a model, are:

(i) Surface condition,
(ii) Liquid crystal stability,
(iii) Liquid crystal purity,
(iv) Application method,
(v) Liquid crystal coating thickness, and
(vi) Lighting and camera/viewing angles.

Recently, Holmes et al (1986) and Gall and Holmes (1986) applied temperature sensitive liquid crystals to in-flight transition studies but, as yet, in-flight shear stress studies using temperature insensitive crystals have not been reported. Having briefly reviewed basic liquid crystal characteristics, the remainder of this sub-section will concentrate on aspects of shear stress quantification for subsonic flows.

Klein and Margozi (1970) devised an instrument for the quantitative shear stress analysis of a liquid crystal compound (reportedly insensitive to temperature). Crystal samples were subjected to rotational shear whilst the dominant scattered light wavelength was observed via a 'grating monochromator' (photomultiplier) yielding a direct relationship between shear stress and wavelength:

Klein and Margozi (1969)

Liquid Crystal Combination

60.00% Cholesteryl nonanoate,
26.75% Cholesteryl chloride,
8.25% Cholesteryl benzoate, and
5.00% Cholesteryl oleyl carbonate.
The experimentally useful indicating range of the tested crystal was determined to be from 0 to 3 g/cm², the shear stress/wavelength relationship being:

\[ T_0 = 0.208\lambda - 119.18, \]

where, \( T_0 \) is shear stress (g/cm²), and \( \lambda \) is scattered light wavelength (nm).

This type of basic shear stress calibration with scattered light wavelength must be a pre-requisite to any complete quantitative global shear stress analysis technique. Unfortunately, however, there remain many uncertainties with regard to both the applicability of such simple shear test devices and the relationship between lighting arrangements and scattered wavelength. As previously mentioned, such factors of interest would particularly appear to be the type and energy distribution of the illumination source and its incidence angle with both the crystals and viewing angle. Further questions that need to be answered involve aspects of shear stress direction (as well as values) using, perhaps, positive and negative relative illumination incidence angles, the possible use of diffraction filters for viewing and the effects of various surface coatings. Assuming that adequate answers to these questions can be resolved and that, for any given crystal compound, a shear stress calibration relationship with scattered light wavelength may be determined, the problem is reduced to the physical quantification of wavelength from visual images. In as much as Klein and Margozi (1970) used a single photomultiplier to observe a single location on their calibration rig, it would seem obvious to use a colour video sensor for global subject observation. Statistical analysis of this colour video signal may, of course, be achieved using video digitisation and aspects of colorimetry.

Elements of colorimetry require precise detailed definitions of terms, such details being related to either psychological and psychophysical concepts, colour perception and colour-matching. From a quantitative viewpoint, colours may be
matched by adding suitable amounts of three fixed primary colours. The choice of three primary colours, though very wide, is not entirely arbitrary, and any set which is such that none of the primaries can be matched by a mixture of the other two may be used. If \( \mathbf{Q} \) is a vector representing a given colour and \( \mathbf{R}, \mathbf{G}, \) and \( \mathbf{B} \) are the vectors representing unit amounts of three fixed primaries, then the vector equation, \( \mathbf{Q} = \mathbf{RR} + \mathbf{GG} + \mathbf{BB} \), states that the given colour is matched by an additive mixture of the quantities \( R, G, B \) of the respective primaries. The scalar multipliers \( R, G, B \) are termed the tristimulus values of colour with respect to the primary set \( \mathbf{R}, \mathbf{G}, \mathbf{B} \). The hypothetical curves shown below illustrate the relative sensitivities of the human eye (cones) to \( R, G, B \) components. Amongst many other sources, colour television theory has been reviewed by Hutson (1971), with aspects of colour measurement and computation being presented by Chamberlin and Chamberlin (1980) and Wyszecki and Stiles (1967).

**Primary System, R=700.0nm, G=546.1nm, B=435.8nm**

Associated with any set of tristimulus values \( R, G, B \) are the chromaticity coordinates \( r, g, b \) defined by:

\[
\begin{align*}
    r &= \frac{R}{R + G + B} \\
    g &= \frac{G}{R + G + B} \\
    b &= \frac{B}{R + G + B}
\end{align*}
\]

It is obvious from these equations that the sum of \( r+g+b \) must always be equal to unity. The \( \mathbf{R}, \mathbf{G}, \mathbf{B} \) system employs monochromatics stimuli at 700.0, 546.1 and 435.8nm as its primaries, chromaticity coordinates being tabulated in
standard tables against wavelength (e.g. 1931 CIE (R,G,B) System, Commission Internationale de l'Eclairage, with further recommendations being made in 1971).

The above description illustrates how colour video signals may be analysed, having been separated into their R, G, B tristimulus values and normalised by their sum to produce chromaticity coordinates. Before discussing the experimental implementation of a true-colour video digitising system, a brief account will be given of a simple study undertaken using shear stress sensitive crystals and the previously described and extensively detailed grey-scale video digitising equipment (section 3.4).

Preliminary liquid crystal experiments were conducted within a closed-return type low-speed wind tunnel at City University, London (Aeronautics Department). The model employed was a smooth, sharp-edged flat plate (Figure 76) with a lateral fence located a short distance from the leading edge producing areas of differing shear stress and a recirculation region. Liquid crystals primarily displaying only changes in red colour intensity were applied to the plate surface and the changes in reflected light intensity with shear stress (previously quantified using Preston tubes) detected using a video 'camcorder'. Experimental data was achieved up to Mach 0.15, the 'red' liquid crystals being insensitive to temperature variations. Subsequent grey-level digitisation of the recorded experimental images made the assumption that the G, B tristimulus values of the crystals could be regarded as constant throughout the study, allowing red component intensity values to be related directly with digitised grey-levels. Whilst such an approximation must be regarded as far from ideal it was necessary because of the limited computational hardware available to this particular study. Selected video images were digitised and those liquid crystal regions corresponding to the locations of the previously conducted Preston tube measurements examined by determining local area light intensity averages. This was achieved by using a
digital zoomed region display programme together with a
pixel intensity histogram analysis, Plate 34 showing a
typical grey-level and pseudo-coloured zoomed region
display. The range of grey-levels present within the zoomed
region typically possessed a histogram of intensities which
had the following form:

![Histogram of Grey-Level Intensities](image)

The major central distribution peak corresponds to liquid
crystal scattered intensities whilst the high intensity,
smaller peak represents bright spots associated with
reflectance from oil flow 'blob' effects. The lower
intensity peak corresponds with the background plate surface
intensity (matt black) where no crystal was present (or had
not been initiated). Ideally, therefore, statistical mean
calculations should compensate for the non-scattered
intensity values allowing a true crystal-associated mean to
be produced. It would appear that most crystal images
exhibit such non-uniform local colour characteristics
(depending on the magnification factor of the lens and
lighting conditions) indicating that some form of
statistical analysis, such as that indicated above, must be
incorporated into any accurate quantification system.

Figure 77 illustrates the average variation of relative
pixel intensity with shear stress, indicating a possible
linear relationship between the two quantities. The two
independent linear gradients indicated in Figure 77 were
achieved from different camera viewing locations, the two
cases being indicative of two different video camera gains
which, because of the totally automatic nature of the
camcorder used, could not be manually controlled. Whilst this grey-level linear relationship with shear stress would appear encouraging, it has little or no practical benefit to a realistic quantification system, general intensity values having no physical relationship to colour wavelength. It is obvious, therefore, that a feasible quantification system must acquire true-colour, R, G, B tristimulus values, from which the appropriate chromaticity coordinates may be calculated.

True-colour video digitisation was achieved via an Imaging Technology RGB-512 module which was integrated with three frame buffer modules (FB-512) to enable real-time image analysis. The RGB-512 module accepts only separate R, G, B video component signals, these being achieved by decoding a standard PAL composite video signal using an Electrocraft Ltd PD-84 PAL video decoder unit. The true-colour video digitisation system is illustrated below.

True-Colour Imaging System

Plate 35 shows a digitised original and zoomed region display for a typical liquid crystal visualization, with Plate 36 showing the separate R, G, B components of the zoomed region. Unfortunately, it is difficult to show the absolute values of the relative colour component intensities
as the photographic process involved in reproducing such images uses automatic exposure control to produce 'good' contrast pictures. Nevertheless, it is obvious that real-time colour pixel values may be simply achieved, which when transformed to chromaticity coordinates may be used to indicate colour wavelength.

In performing such colour analyses it would seem appropriate to consider the colour distribution of specified local regions of the image in a similar manner to that previously described for the grey-level analysis system, accounting for both background and reflected bright spot errors. It would also seem appropriate to re-iterate the importance of digitisation bit level and colour intensity with respect to both the accuracy and repeatability of such an analysis system. For a video tape signal a maximum of 5 bits (to provide 'noise-free' data) per colour channel (R, G, B) should be used per signal field acquisition (32 digitisation levels), a good quality video camera should typically produce 6-bit images (64 levels). To achieve reliable 8-bit images, with a full 256 digitisation level range per colour channel, the incoming images should be digitally averaged (real-time, weighted-averaging having been illustrated in section 7.7). The relative accuracy of the chromaticity coordinates must also be examined with respect to colour brightness (indicated by the original R, G, B values). As an example, consider the following chromaticity coordinates; r=0.0, g=0.5, and b=0.5. From an input range of 0 to 255 the tristimulus values that produce such ratios may range from 0, 1, 1 (R, G, B) to 0, 255, 255. An error of only ±1 in these channel values will wildly influence the accuracy of the 0, 1, 1 case whilst hardly influencing the ratios of the 0, 255, 255 case. From a physical viewpoint this error is equivalent to considering the actual signal-to-noise ratios of each colour channel signal, the errors associated with very low component signals being significant. Having briefly examined the possible system factors that may affect the quantification accuracy, the remainder of this sub-section will outline possible analysis procedures in more detail.
The most important system design characteristics associated with a possible true-colour/shear stress quantification programme must inevitably be its ease of use, speed and efficiency, combined with experimental accuracy and clearly presented results. Initially, it would seem appropriate to consider two basic systems, real-time/on-line or whole field global presentation. The real-time system would present continuous local region statistics as an on-line function, mean shear stress values from a number of specified local interest regions being continuously monitored and output as either graphical or continuous plotter information. Such a system would initially require repeatedly replaying a particular tape sequence a number of times to enable global data for a whole image to be acquired (each run examining a specified image region).

The alternative global examination procedure would examine a 24-bit (8 bits per colour channel) digitally averaged image, calculate each pixel's shear stress value from its chromaticity coordinates and reassign each pixel a value proportional to the computed shear stress, allowing the entire shear stress distribution to be displayed as pre-defined false-colours (as opposed to pseudo-colours which are defined for grey-level images). Preliminary results illustrating this approach are shown in Plate 37 which presents an original liquid crystal visualization (non-averaged and analysed only to 15-bit accuracy, i.e. 5 bits per colour channel) with the indicated area of interest zoomed and re-displayed as false-colours (representing wavelength). The transformation from pixel chromaticity to wavelength was achieved within a few seconds, the eventual further transformation into shear stress being achievable within similar time constraints.

Unfortunately, a realistic shear stress display could not be achieved without accurate shear stress/wavelength calibration data and more involved computing algorithms to 'mask' undesired background data and accommodate initial plate illumination details. Whilst it is envisaged that this
technique may eventually enable a simple shear stress representation of a complete visualized field, a major limitation would be concerned with how to economically (and efficiently) store the results. A true-colour 512 * 256 pixel resolution image (24 bits per pixel) occupies almost 0.75 Megabytes of disk storage, that is to say, the entire capacity of a double-sided, double density 5.25 inch floppy diskette. For a typical experiment it would, of course, be desirable to perform such a shear stress transformation every few seconds, requiring the analysed shear stress displays to be recorded onto tape or, more realistically, an optical disk. Such a procedure would then allow shear stress contours and temporal/spatial variations to be monitored as an enhanced 'movie' when replayed in pseudo real-time (plus the analysis of single images in a more quantitative manner). A true real-time shear stress display system could possibly be achieved via dedicated hardware facilities (parallel processors, etc.).

This brief discussion has demonstrated the various experimental requirements and limitations associated with global quantitative shear stress analyses using liquid crystal visualizations. Whilst the suggestions made to-date have been of a preliminary nature, the Author's experience in real-time digital image analysis and processing would seem to suggest that the proposals outlined may be readily achieved using the technology now available to minicomputer-based image processing systems. These suggestions do, however, rely on adequate liquid crystal calibration information and the importance of the physical characteristics associated with the illumination and scattering properties of the crystal compounds must be both appreciated and investigated. Having established these characteristics it would appear that the benefits to be gained from future shear stress analyses are tremendous and the possible use of digital image analysis in this respect could facilitate truly global quantitative information.
7.9 Summary

This chapter has briefly examined some of the aspects of digital image processing associated with the enhancement of flow visualization images. In addition to this image processing introduction, further examples of real-time image analysis have been included to demonstrate the further capabilities of the 'digital imaging technique'. The quantitative analyses examined the frequency of secondary vortices associated with the vortex shedding from a circular cylinder and, in addition, has been used to produce an intermittency map of a turbulent jet issuing into a uniform crossflow. These quantitative investigations proved to be very expedient methods of examining the turbulent flow models in question and, in particular, demonstrated the applicability of the imaging technique to three-dimensional complex flows.

Further investigations of a more qualitative nature were reported for other flow models, these being boundary layer modification by passive means (LEBUs) and dynamic stall on a pitching aerofoil. Digital imaging hardware enhancements also allowed real-time image processing routines to be applied to vapour-screen visualizations with true-colour video digitisation being applied to shear stress sensitive liquid crystal visualizations. These latter investigations have applied state-of-the-art imaging hardware to flow images with a view to further implementing digital imaging techniques in a multitude of fluid mechanics problems. Indeed, the true-colour video digitisation technique reported in this chapter would itself appear promising enough to encourage much further work along such lines.
The primary objective of the work presented in this thesis has been to examine the possibility of extracting statistical data from smoke-visualized turbulent flows. This undertaking was accomplished through the implementation of a real-time digital image analysis approach, referred to as the 'digital imaging technique'. Quantitative analyses achieved using the digital imaging technique have been carefully compared with, as far as possible, equivalent experimental results from traditional hot-wire anemometry sensors, with a generally good correlation being observed between the comparable data. The specific statistical comparisons were accomplished for the turbulent wake of a two-dimensional flat plate model and included the following investigative topics:

(i) Intermittency Measurements,
(ii) Autocorrelation Functions and Spectral Analyses,
(iii) Spatial Correlations,
(iv) Wake Interface Statistics, and
(v) Mean Fluctuating Turbulence Quantities.

Before drawing to a general conclusion with regard to the digital imaging technique as an experimental research tool, the following paragraphs will conclude the results obtained in each of the above-listed comparative topics.

Intermittency

The digital imaging technique was capable of producing repeatably accurate intermittency functions over the majority of the turbulent wake region. The technique did, however, produce marginally erroneous intermittency factors in flow regions of particularly high or low smoke contaminant concentrations (and hence light intensity) due
primarily to the limited sensitivity range of the image sensor. This limited sensitivity was not a specific problem associated with the particular image sensor (CCD video device) used for this study, but would appear an unavoidable characteristic of video image sensors in general. The restrictive nature of the sensitivity range limited the detection ability of the system where both very high and very low image intensities were present, although in the present study, the latter was also a function of the relatively low power laser source used for illumination purposes. Further investigations involving interface crossing frequencies (to be concluded later in this chapter) revealed an inability of the hot-wire sensor digital turbulence discriminator to correctly identify irrotational fluid regions within otherwise fully turbulent flows. The digital imaging intermittency functions therefore offered quantitative evidence of hot-wire system intermittency factor overestimations, these being due to both the discriminatory inability and a certain degree of system noise. The overall agreement between the digital imaging and hot-wire intermittency functions was, however, good and with appreciation of all of the above-mentioned error sources, the digital imaging technique could reasonably be experimentally applied to turbulent intermittency studies.

**Autocorrelation Functions and Spectral Analyses**

Comparative results obtained from digital imaging and hot-wire spectral analyses were found to correctly identify the Strouhal vortex shedding frequencies behind the flat plate model to within an accuracy of 0.05 Hz. The low sampling rate of the digital imaging technique, although limiting in upper frequency detection capability (Nyquist frequency of 25.0 Hz) also produced regular evidence of low-frequency contributions to the vortex shedding which, being confirmed through hot-wire autocorrelation functions, were tentatively identified as the result of vortex shedding frequency fluctuations. Although the digital imaging technique provided a non-intrusive analysis tool, detecting
the flow period both through interface and structure intensity fluctuations, the method was somewhat restricted due to the low sampling frequency associated with standard video equipment. This limitation does not appear to be a major problem as the variable-format scanning capabilities of the latest generation of solid state video devices would allow partial-field scanning rates of the order of thousands of Hertz, sufficient to detect a wide range of experimental flow-associated frequencies. Such a facility was not incorporated into the study presented within this thesis but would appear relatively simple to achieve for future studies of this nature.

**Spatial Correlations**

The spatial correlation function achieved by hot-wire sensors was not conducted under identical conditions to those experiments undertaken with the digital imaging technique and is, therefore, only indicative of the expected vortex spacing and integral length scales for a typical flat plate model. The vortex spacing distance obtained by the digital imaging technique itself was found to require very accurate calibration of the image sensor with absolute distance. Having achieved this initial calibration, however, the vortex spacing distance compared very well with that expected both from experimental and alternative sources of published data. The integral length scale, on the other hand, was found to be dependent on the degree of image blur, which having established the object (vortex) velocity across the image, could be calculated and used to produce a suitably corrected length scale. The ease with which digital imaging spatial correlations could be achieved enabled many more spatial investigations which, as far as possible, were found to compare favourably with previously reported values.
**Wake Interface Statistics**

Detailed comparisons between the digital imaging and hot-wire wake interface crossing frequencies revealed an inability of the hot-wire digital turbulence discriminator to correctly identify irrotational fluid regions amongst otherwise turbulent flows. This was established due to the ability of the digital imaging technique to label wake interfaces as either 'outer' or 'inner' encounters, no equivalent procedure being possible using a single hot-wire probe. The digital imaging technique was also able to quantify the distribution of the number of interface pairs encountered at any particular downstream wake location. This so-called interface multi-valuedness, whilst being important for theoretical and computational descriptions of the interface characteristics, would be very difficult to achieve using even a complex array of hot-wire sensors.

**Mean Fluctuating Turbulence Quantities**

Preliminary investigations would appear to indicate that the digital imaging technique was capable of producing relative distributions of fluctuating image intensities which, when combined with the turbulent intermittency function and normalised against known turbulence levels, could be used to obtain global turbulence intensity distributions.

The possible expansion of this particular aspect of the digital imaging technique, together with the relative benefits associated with all of the other aforementioned measurements, into a fully two-dimensional system would appear extremely promising. A preliminary analysis of the possible difficulties involved in such a proposed system was, however, found to be slightly less encouraging, the previously mentioned image sensor limitations serving to affect potential system performance. It was not possible to investigate these pre-conceived and possibly speculative restrictions through experimental studies and as such they must remain intuitive conjecture on behalf of the Author.
Further investigations using the digital imaging technique were undertaken into the secondary vortex shedding associated with wake of a circular cylinder and the intermittency analysis of a turbulent jet issuing into a uniform crossflow. Secondary shear layer instability frequencies were successfully quantified using the visualization technique which, being a non-intrusive method, appeared far more desirable than alternative intrusive detection methods such as hot-wire anemometry. Unfortunately, a detailed investigation of this model was not achievable due to the limited sampling frequency of the imaging technique. The results obtained in this respect, even over the limited Reynolds number range available were, however, very encouraging and indicated possible advantages of the digital technique for such a study, as well as revealing details of the secondary vortex frequency dependency on base pressure (demonstrated through base-bleed variations). The intermittency analysis of the turbulent jet in a crossflow was achieved very quickly and, although not directly comparable with alternatively quantified results, the intermittency map produced would nevertheless appear to correspond very well to the visualized details of the mean jet profile. This latter investigation illustrated the applicability of the imaging technique to complex, three-dimensional flows where the expedient nature of the analysis method would appear to be an invaluable experimental asset.

Although the foregoing discussions have related the findings of the individually listed topics associated with the digital imaging technique, it must be appreciated that all of these results may be acquired from only one, single experimental analysis. That is to say, it would be possible to perform a single one hundred second experiment on the turbulent flat plate model wake and, from the data collected, produce an intermittency function, analyse the vortex shedding frequency (using wake interface or structure intensity fluctuations), calculate the spatial correlation function (albeit in a transverse direction, as opposed to the normally acquired longitudinal information), determine
the distribution of the outer and inner wake interfaces and produce a distribution of the fluctuating intensity values. Whilst this may appear to be an obvious statement, the individual nature of the discussions and conclusions may not immediately accentuate this particular system attribute.

The overall performance and viability of the digital imaging technique as an on-line experimental research tool must be assessed with respect to both cost and efficiency. The technique does, for instance, demand the continuous seeding of a turbulent flow with smoke, for which a specialised smoke tunnel would ideally be required, although exhausting a simple, open-return tunnel to the atmosphere would also suffice. The illumination source used for the present study may be adequate for a variety of flow models but could obviously be improved with an increased power rating of perhaps 25 mW (Helium-Neon), although this also increases the necessity for strict safety controls and extra precautions with regard to laser alignment. The most specialised facility required is, however, the combination of an 'intelligent' solid state video device and a real-time digital imaging analysis system. Whilst the cost of the imaging system and host minicomputer for the present study was of the order of twenty thousand pounds sterling (purchased in 1984), modern state-of-the-art equivalent systems have developed enormously over the last three years (1985-1988). It would, for instance, now be possible to undertake similar analysis techniques on smaller, less expensive machines for a total cost of, perhaps, less than five thousand pounds sterling, an outlay comparable with that required for a single hot-wire anemometer system. Having established the overall cost of the imaging technique it would appear to offer an extremely economic and expedient means of extracting turbulent flow data. The technique does not, however, provide mean or instantaneous local velocity information and the presented turbulence intensity investigations require greater study in order to be conclusive. Accepting these cautionary warnings the digital imaging technique would appear an invaluable aid to
turbulent, intermittent flow studies, with particular advantages being possible for investigations involving both auto- or spatial correlations and wake interface statistics. The detailed comparative studies recorded in this thesis graphically illustrate how days of hot-wire traversing could be effectively replaced with less than an hour of digital imaging analyses. It is, therefore, the Author's personal opinion that where demand for the appropriate statistical data exists, the digital imaging technique, at its present state of development, would prove to be a very cost-effective experimental tool. It would also seem very likely that further applications for a real-time digital imaging technique would be found once the basic capabilities of this system were appreciated by the research community.

Additional Experimental Investigations

In addition to the aforementioned capabilities of the so-called 'digital imaging technique', Chapter Seven of this thesis illustrated further applications of digital imaging technology to the realm of flow visualization. The most evident feature of these brief, but illustrative, studies is the diversity of the applications, incorporating mean digital flow images, possible vortex development extraction, real-time composite image enhancement for high-speed flows and preliminary, quantitative global surface shear stress analyses. Whilst all of these techniques have their own individual merits, the latter investigation involving shear stress sensitive liquid crystals would appear to offer a very promising enhancement to an experimental technique presently receiving a great deal of attention. Certainly, the enormous benefits of a global shear stress visualization technique would be multiplied manifold by a suitable, efficient yet cost-effective quantitative analysis procedure. Once again, it is the Author's belief that the preliminary analyses reported in this thesis are sufficient to indicate that true-colour digital image analysis may play an important, if not crucial, role in the exploitation of
these shear stress sensitive crystals with respect to practical quantitative analyses.

The discussions and conclusions concerning the investigations reported in this thesis inevitably lead to a number of recommendations for further work in this field. Before proposing a number of possible future studies it would, however, seem appropriate to briefly summarise the overall concept of this thesis as this may itself initiate new ideas and proposals quite separate from those related directly to the presented flow studies.

The preliminary catalyst to the work presented in this dissertation was the desire to obtain quantitative statistics from flow visualization images. The desire was primarily fulfilled through the development of a real-time digital image analysis technique for smoke-visualized turbulent flows. Having witnessed the possible capabilities of a real-time digital imaging system, the study developed into alternative applications in which digital imaging has enabled enhanced visualization techniques and the possible quantitative analysis of visualization methods indicative of specific flow quantities (i.e. shear stress). The resultant philosophical approach to all visualization techniques involving the continuous analysis or display of developing flow phenomena would therefore be best described as:

(a) Identify the physical characteristics associated with the visualization technique that could possibly be quantified,

(b) Retrieve limited, but relevant, information from the visualized images to allow time- or space-dependent characteristics to be quantified in real-time, and

(c) Compare, where possible, quantitative imaging results directly with equivalent information obtained by traditional anemometer (or pertinent device) before applying to alternative flow model studies.
The experimental requirement for speed and efficiency is paramount, especially where data sample populations are required to number tens or even hundreds of thousands. Expedience may, however, be ensured by maintaining an on-line, real-time analysis approach. Although this may inevitably allow the examination of only a limited number of flow features within each acquired image field, a complex, full-field, in-depth analysis study of each individual visualization would become time-consuming and inefficient at producing meaningful statistical data. Therefore, the crucial aspect of any quantitative visual imaging technique may be proposed as being its practical, on-line application which without further storage or retrieval, yields directly meaningful statistical data.

Having summarised the overall philosophical concept of this thesis the final paragraphs of this chapter will outline the Author's recommendations for future work.

Future Studies

With regard to the digital imaging technique reported in this dissertation, the most restrictive aspect of its application to general fluid mechanics studies is its limited sampling frequency (50 Hz). Whilst some degree of limitation was inevitable for an initial study, in which it was essential to use standard video equipment to restrict the original expense of such a speculative technique, any initial doubts regarding the applicability of the imaging technique have been subsequently eradicated. With regard to possible system improvements, it is proposed that an 'intelligent' solid state CCD sensor of medium resolution (say 512(H) * 512(V) picture elements) should be interfaced to a modern, state-of-the-art video digitisation system. The proposed system should be capable of variable-field scanning and analysis in real-time, offering a maximum sampling rate of the order of one thousand Hertz, combined with variable integration time capabilities to allow 'snap-shot' full-field acquisitions at alternative output frequencies. The
ability to display the scanned image, regardless of acquisition frequency, would be of obvious benefit to such a system, although by no means an essential attribute.

In addition to sensor-based improvements it would appear that recent developments with respect to computer hardware may also prove to be an important system modification for future studies. In particular, there have been notable advances in the area of array processing where new products such as the 'transputer' offer immense processing capabilities at an ever-decreasing cost. Certainly all of the analysis procedures developed in this thesis for the imaging technique could be theoretically applied to a complete two-dimensional image array. Real-time array processing could, therefore, realise the processing speed required to enable this next possible modification to be undertaken. The total cost of the any future arrangement should, of course, always reflect the relative system capabilities with respect to an existing single-processor system.

Specific experimental studies that the present work has indicated could be further investigated using the digital imaging technique in its revised arrangement, include continuance with regard to secondary vortex shedding frequencies and the intermittency mapping of the jet in a crossflow configuration. Whilst an in-depth quantitative digital imaging analysis of the secondary vortices associated with the vortex shedding from a circular cylinder would be of obvious value to the previous studies reported by Bloor (1964) and Wei and Smith (1986), the effect of base-bleed on the secondary vortices would also appear to require further investigation as this would possibly confirm the independence of the secondary and Strouhal vortex shedding phenomena. The turbulent jet issuing into a crossflow would appear to be a complex, three-dimensional flow model which is, at present, actively being investigated (including a project being conducted in the Department of Civil Engineering on behalf of the Royal Aerospace Establishment (formerly the Royal Aircraft Establishment),
Farnborough). It would seem reasonable to assume that thorough investigation of the intermittency profiles associated with the developing jet structure may, therefore, also be a potential application for the digital imaging technique. Recent interest in multiple jet configurations, which exhibit complex interactive flowfields would, of course, also benefit from this approach.

Further applications of digital imaging as a flow visualization enhancement technique were also presented for the study of boundary layer manipulation and dynamic stall on an aerofoil. The investigations reported appear to demonstrate that digital imaging may constructively aid the analysis of manipulated boundary layers, particularly in assessing the mean flow effects of devices, such as LEBUs (Large Eddy Break-Up Devices) or riblets, on a developing boundary layer. In addition, preliminary dynamic stall visualizations also seem to indicate that future work involving simultaneous flow visualization, local pressure and/or strain-gauge total lift and drag measurements could also be more thoroughly analysed through digital imaging analyses of the dynamic vortex. From an image enhancement aspect, the vapour-screen visualizations/cumulative imaging approach demonstrates the applicability of digital image processing to relatively stationary, low-contrast flow visualization techniques, which could be extended to provide an on-line enhancement system. Finally, it would seem most desirable to develop the capabilities of a real-time real-colour quantification technique for the study of global shear stress distributions using liquid crystal technology. Advancements in this aspect of digital imaging appears most encouraging and, following initial investigations, has inspired positive enthusiasm amongst fellow researchers.

It should be emphasized that real-time digital image analysis, particularly of true-colour images, has only recently (over the last decade) been achievable under laboratory conditions (including cost, computer size and system flexibility). The ever-increasing capabilities of
high-technology equipment must be fully investigated whenever possible. Having discovered its capabilities and limitations, demands for specific improvements must be forthcoming from the scientific domain. As would often appear the case, the 'final solution' is never achieved from a development system. Instead, the completion of a project indicates the basis for such a solution, the technological advances realised during the project's duration being immediately applicable to the next development system. It is hoped that the work undertaken by the Author over his five years of experimental study has fulfilled these obligations with regard to digital image analysis in flow visualization experiments and that future developments in this field will benefit from these initial undertakings.
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Plate 33. Liquid Crystal Shear Stress Flow Visualization

(Courtesy of L. Gaudet, R.A.E. Bedford)
Plate 34. Liquid Crystal Shear Stress Flow Visualization
Grey-Level Digitisation plus Pseudo-Coloured Zoom
Plate 35. Liquid Crystal Shear Stress Flow Visualization True-Colour Digitisation plus Zoomed Display
Plate 36. Liquid Crystal Shear Stress Flow Visualization
True-Colour Digitisation Colour Components
Plate 37. Liquid Crystal Shear Stress Flow Visualization
Wavelength Quantification and Display
Figure 1. Schematic of Smoke Tunnel

Figure 2. Smoke Tunnel Static Pressure Relationship
Figure 3. Schematic of One-Dimensional Probe Traverse

Figure 4. Schematic of Three-Dimensional Probe Traverse
Figure 5. Schematic of Boundary Layer Tunnel

Figure 6. Smoke Tunnel Flat Plate Cross-Section
Section B

Pressure Tappings (5.0 Spacing)

Pressure Tubing (Recessed)

All Dimensions in mm.

Figure 7. Boundary Layer Tunnel Flat Plate Cross-Section

Figure 8. Typical Hot-Wire Calibration Curve
Figure 9. Schematic of Smoke Introduction System

Figure 10. Schematic of Laser Mount and Traversing Unit
Figure 11. Schematic of Laser Scanner Controller Circuit
Figure 12. Schematic of CCD Camera Mount and Traversing Unit

Pressure

\[ \begin{align*}
A & \text{ Reynolds No.: } 2.73 \times 10^4 \\
\text{Reynolds No.: } 1.36 \times 10^4 & \text{ Location: } 0.0 \% D
\end{align*} \]

Figure 13. Flat Plate Surface Pressure Distribution
Figure 14. Spanwise Base Pressure Distribution

Figure 15. Hot-Wire Wake Spatial Correlation (Spanwise)
Figure 16. Mean Wake Centreline Static Pressure Distribution

Reynolds No.: $1.36 \times 10^4$

Peak Location: 1.125 X/D

- Static Pressure

Pressure Coefficient (Cp)
Mean Longitudinal Velocity ($U/U_{ref}$)

Mean Longitudinal Turbulence Intensity (%)

Reynolds No.: $1.36 \times 10^4$
Location: $1.125 \times X/D$

-3.0 -2.0 -1.0 0.0 1.0 2.0 3.0

Y/D Location

---

Figure 17a. Longitudinal Turbulence Intensity (Min. Static Press)

---

Figure 17b. Longitudinal Velocity (Min. Static Pressure)
Figure 17c. Longitudinal Velocity Skewness (Min. Static Pressure)

Reynolds No.: $1.36 \times 10^4$
Location: $1.125 \times D$

- Hot-Wire

Figure 17d. Longitudinal Velocity Kurtosis (Min. Static Pressure)

Reynolds No.: $1.36 \times 10^4$
Location: $1.125 \times D$

- Hot-Wire
Figure 18a. Hot-Wire Mean Velocity and Turbulence Intensity
Reynolds No.: $1.36 \times 10^4$
Location: $4.0 \times X/D$

Symbols only shown where different from isolated case

Figure 18b. Hot-Wire Mean Velocity and Turbulence Intensity
Reynolds No.: $1.36 \times 10^4$
Location: $6.0 \times D$

Symbols only shown where different from isolated case

**Figure 18c. Hot-Wire Mean Velocity and Turbulence Intensity**
Figure 18d. Hot-Wire Mean Velocity and Turbulence Intensity

Reynolds No.: $1.36 \times 10^4$
Location: 8.0 X/D

Symbols only shown where different from isolated case

- Isolated Plate
- Plate + Smoke Tube
- Plate/Smoke Tube + Bleed
Reynolds No.: $1.36 \times 10^4$
Location: $10.0 \times D$

Figure 18e. Hot-Wire Mean Velocity and Turbulence Intensity
Reynolds No.: $1.36 \times 10^4$
Location: $12.0 X/D$

Figure 18f. Hot-Wire Mean Velocity and Turbulence Intensity
Figure 19a. Hot-Wire Mean Wake Centreline Velocity

- Wisby - Reynolds No.: $1.36 \times 10^4$
- Bradbury (1976) - Reynolds No.: $2.56 \times 10^4$

Figure 19b. Hot-Wire Mean Wake Centreline Turbulence Intensity
Intermittency Factor

Reynolds No.

Reynolds No.

Reynolds No.
Hot-Wire

Threshold Level Chosen (0.2%)

Figure 20. Freestream Intermittency Factor vs Threshold Level
Figure 21a. Hot-Wire Zonal Mean Velocities

Reynolds No.: $1.36 \times 10^4$
Location: 12.0 X/D

Figure 21b. Hot-Wire Zonal Mean Turbulence Intensities

Reynolds No.: $1.36 \times 10^4$
Location: 12.0 X/D
Figure 21a. Hot-Wire Zonal Mean Velocities

Figure 21b. Hot-Wire Zonal Mean Turbulence Intensities
Figure 22a. Transverse Distribution of 'Non-Turbulent' Intensity

Reynolds No.: $1.36 \times 10^4$
Location: 2.0 X/D

Figure 22b. Transverse Distribution of 'Non-Turbulent' Intensity

Reynolds No.: $1.36 \times 10^4$
Location: 4.0 X/D
Figure 22c. Transverse Distribution of 'Non-Turbulent' Intensity

Figure 22d. Transverse Distribution of 'Non-Turbulent' Intensity
Reynolds No.: $1.36 \times 10^4$
Location: 10.0 X/D

Figure 22e. Transverse Distribution of 'Non-Turbulent' Intensity

Reynolds No.: $1.36 \times 10^4$
Location: 12.0 X/D

Figure 22f. Transverse Distribution of 'Non-Turbulent' Intensity
Figure 23a. Pixel and Hot-Wire Intermittency Functions

Figure 23b. Pixel and Hot-Wire Intermittency Functions
Reynolds No.: $1.36 \times 10^4$
Location: 6.0 X/D
- Digital Imaging
- Hot-Wire

Figure 23c. Pixel and Hot-Wire Intermittency Functions

Reynolds No.: $1.36 \times 10^4$
Location: 8.0 X/D
- Digital Imaging
- Hot-Wire

Figure 23d. Pixel and Hot-Wire Intermittency Functions
Figure 23e. Pixel and Hot-Wire Intermittency Functions

Figure 23f. Pixel and Hot-Wire Intermittency Functions
Figure 24. Pixel and Hot-Wire Intermittency Functions

Figure 25. Pixel and Hot-Wire Intermittency Functions
Reynolds No.: $6.83 \times 10^3$
Location: 2.0 X/D
Plate Incidence: 90 degrees

Figure 27a. Digital Imaging Autocorrelation and Spectral Analyses
Reynolds No.: $1.36 \times 10^4$
Location: $2.0 \times D$
Plate Incidence: 90 degrees

Figure 27b. Digital Imaging Autocorrelation and Spectral Analyses
Correlation Factor

Reynolds No.: 2.05 * 10^4
Location: 2.0 X/D
Plate Incidence: 90 degrees

Digital Imaging

Peak Frequency: 18.24 Hz
Spectral Intensity: 1.35

Digital Imaging

Peak Frequency: 18.24 Hz
Spectral Intensity: 1.26

Figure 27c. Digital Imaging Autocorrelation and Spectral Analyses
Reynolds No.: 2.73 * 10^4
Location: 2.0 X/D
Plate Incidence: 90 degrees

Figure 27d. Digital Imaging Autocorrelation and Spectral Analyses
Reynolds No.: $6.82 \times 10^3$
Location: 2.0 X/D
Plate Incidence: 90 degrees

Figure 28a. Hot-Wire Autocorrelation and Spectral Analyses
Reynolds No.: $1.36 \times 10^4$
Location: 2.0 X/D
Plate Incidence: 90 degrees

Peak Frequency: 12.10 Hz
Spectral Intensity: 1.12

Peak Frequency: 12.10 Hz
Spectral Intensity: 2.33

Figure 28b. Hot-Wire Autocorrelation and Spectral Analyses
Reynolds No.: $2.05 \times 10^4$
Location: $2.0 \times X/D$
Plate Incidence: 90 degrees

Figure 28c. Hot-Wire Autocorrelation and Spectral Analyses
Reynolds No.: $2.73 \times 10^4$
Location: 2.0 X/D
Plate Incidence: 90 degrees

Figure 28d. Hot-Wire Autocorrelation and Spectral Analyses
Figure 29. Shedding Frequency Relationship with Reynolds Number

Figure 30. Strouhal Number Relationship with Reynolds Number
Figure 31. Pixel Fluctuation Frequency Spectral Intensities

Reynolds No.: $1.36 \times 10^4$

Digital Imaging

- 24.2 Hz Component
- 12.1 Hz Component

Locus of Maximum Spectral Intensity
Reynolds No.: $1.36 \times 10^4$
Location: 6.0 X/D

Hot-Wire, Sampling Rate: 244.2 Hz

- 24.2 Hz Component
- 12.1 Hz Component

Peak Intensity

Figure 32. Hot-Wire Shedding Frequency Spectral Intensities
Reynolds No.: $1.36 \times 10^4$
Location: 2.0 X/D
Plate Incidence: 90 degrees

Figure 33a. Digital Imaging Autocorrelation and Spectral Analyses
Figure 33b. Digital Imaging Autocorrelation and Spectral Analyses
Reynolds No.: $1.36 \times 10^4$
Location: $2.0 \times \frac{X}{D}$
Plate Incidence: 70 degrees

Figure 33c. Digital Imaging Autocorrelation and Spectral Analyses
Reynolds No.: $1.36 \times 10^4$
Location: 2.0 X/D
Plate Incidence: 60 degrees

Figure 33d. Digital Imaging Autocorrelation and Spectral Analyses
Reynolds No.: $1.36 \times 10^4$
Location: 2.0 X/D
Plate Incidence: 50 degrees

Figure 33e. Digital Imaging Autocorrelation and Spectral Analyses
Reynolds No.: $1.36 \times 10^4$
Location: 2.0 X/D
Plate Incidence: 40 degrees

Figure 33f. Digital Imaging Autocorrelation and Spectral Analyses
Reynolds No.: $1.36 \times 10^4$
Location: 2.0 X/D
Plate Incidence: 30 degrees

Figure 33g. Digital Imaging Autocorrelation and Spectral Analyses
Reynolds No.: $1.36 \times 10^4$
Location: 2.0 X/D
Plate Incidence: 90 degrees

Figure 34a. Hot-Wire Autocorrelation and Spectral Analyses
Reynolds No.: $1.36 \times 10^4$
Location: 2.0 X/D
Plate Incidence: 80 degrees

Sampling Rate: 244.2 Hz
Sampling Rate: 60.1 Hz

Peak Frequency: 12.30 Hz
Spectral Intensity: 0.92

Peak Frequency: 12.35 Hz
Spectral Intensity: 2.40

Figure 34b. Hot-Wire Autocorrelation and Spectral Analyses
Reynolds No.: $1.36 \times 10^4$
Location: 2.0 X/D
Plate Incidence: 70 degrees

Figure 34c. Hot-Wire Autocorrelation and Spectral Analyses
Figure 34d. Hot-Wire Autocorrelation and Spectral Analyses
Reynolds No.: $1.36 \times 10^4$
Location: 2.0 X/D
Plate Incidence: 50 degrees

Peak Frequency: 16.40 Hz  
Spectral Intensity: 0.95

Peak Frequency: 16.50 Hz  
Spectral Intensity: 2.26

Figure 34e. Hot-Wire Autocorrelation and Spectral Analyses
Correlation Factor

Reynolds No.: $1.36 \times 10^4$
Location: $2.0 \times D$
Plate Incidence: 40 degrees

Sampling Rate: 60.1 Hz

Sampling Rate: 244.2 Hz

Peak Frequency: 19.90 Hz
Spectral Intensity: 1.07

Peak Frequency: 19.95 Hz
Spectral Intensity: 1.60

Figure 34f. Hot-Wire Autocorrelation and Spectral Analyses
Correlation Factor

Reynolds No.: $1.36 \times 10^4$
Location: 2.0 X/D
Plate Incidence: 30 degrees

Sampling Rate: 244.2 Hz
Sampling Rate: 60.1 Hz

Peak Frequency: 27.70 Hz
Peak Frequency: 28.95 Hz
Spectral Intensity: 0.39
Spectral Intensity: 1.18

Figure 34g. Hot-Wire Autocorrelation and Spectral Analyses
Reynolds No.: $1.36 \times 10^4$

- Digital Imaging

![Graph showing shedding frequency relationship with incidence angle.]

**Figure 35. Shedding Frequency Relationship with Incidence Angle**

- Digital Imaging
- Fage and Johansen (1927a)
- Hoole (1968)

$$St = f \times \frac{D}{U_0}$$

![Graph showing Strouhal number relationship with incidence angle.]

**Figure 36. Strouhal Number Relationship with Incidence Angle**
Reynolds No.: $1.36 \times 10^4$
Fixed Probe Location: 2.0 Y/D
Movable Probe Locations: > 2.0 X/D, > 2.0 Y/D

Figure 37. Hot-Wire Spatial Correlation
Plate Incidence: 90 degrees
4.8mm Focal Length Lens - Side Window Viewing

Digital Imaging

Reynolds No.: 2.72 \times 10^4, L(x) = 1.107 D
Reynolds No.: 1.36 \times 10^4, L(x) = 0.830 D
Reynolds No.: 6.82 \times 10^3, L(x) = 0.770 D

Figure 38. Digital Imaging Spatial Correlations - Side Viewing
Plate Incidence: 90 degrees
8.5mm Focal Length Lens - Glass Floor Viewing

Digital Imaging

\[ \text{Reynolds No.: } 2.05 \times 10^4, \quad L(x) = 0.900 \text{ D} \]
\[ \text{Reynolds No.: } 6.82 \times 10^4, \quad L(x) = 0.775 \text{ D} \]

Figure 39. Digital Imaging Spatial Correlations - Floor Viewing
Reynolds No.: $1.36 \times 10^4$
Plate Incidence: 90 degrees

Digital Imaging
- Integration Period 20 mS, $L(x) = 0.830$ D
- Integration Period 16 mS, $L(x) = 0.810$ D
- Integration Period 8 mS, $L(x) = 0.770$ D

Figure 40. Imaging Spatial Correlations - Variable Integration
Reynolds No.: $1.36 \times 10^4$
Plate Incidence: 90 degrees

Digital Imaging

- Pixel Spatial Correlation
- 'Intermittency' Spatial Correlation

$L(x) = 0.80 \, Dn$

Figure 41a. Digital Imaging Spatial Correlation at Incidence

Reynolds No.: $1.36 \times 10^4$
Plate Incidence: 80 degrees

Digital Imaging

- Pixel Spatial Correlation
- 'Intermittency' Spatial Correlation

$L(x) = 0.81 \, Dn$

Figure 41b. Digital Imaging Spatial Correlation at Incidence
Reynolds No.: $1.36 \times 10^4$
Plate Incidence: 70 degrees

Digital Imaging
- --- Pixel Spatial Correlation
- --- 'Intermittency' Spatial Correlation

$L(x) = 0.90 Dn$

Distance (mm)

Figure 41c. Digital Imaging Spatial Correlation at Incidence

Reynolds No.: $1.36 \times 10^4$
Plate Incidence: 60 degrees

Digital Imaging
- --- Pixel Spatial Correlation
- --- 'Intermittency' Spatial Correlation

$L(x) = 1.04 Dn$

Distance (mm)

Figure 41d. Digital Imaging Spatial Correlation at Incidence
Reynolds No.: $1.36 \times 10^4$
Plate Incidence: 50 degrees

Digital Imaging

Pixel Spatial Correlation

'Intermittency' Spatial Correlation

Figure 41e. Digital Imaging Spatial Correlation at Incidence

Reynolds No.: $1.36 \times 10^4$
Plate Incidence: 40 degrees

Digital Imaging

Pixel Spatial Correlation

'Intermittency' Spatial Correlation

Figure 41f. Digital Imaging Spatial Correlation at Incidence
Reynolds No.: $1.36 \times 10^4$
Plate Incidence: 30 degrees

Digital Imaging
- - - Pixel Spatial Correlation
- - - 'Intermittency' Spatial Correlation

$L(x) = \text{---- Dn}$

Figure 41g. Digital Imaging Spatial Correlation at Incidence
Reynolds No.: $1.36 \times 10^4$
Location: 6.0 X/D

Digital Imaging
- 'Outer Interface' Edges
- 'Ensemble Interface' Edges

Figure 42. Digital Imaging and Hot-Wire Crossing Frequencies
Reynolds No.: $2.73 \times 10^4$
Location: $6.0 \times X/D$

Digital Imaging
- 'Outer Interface' Edges
- 'Ensemble Interface' Edges

Figure 43. Digital Imaging and Hot-Wire Crossing Frequencies
Reynolds No.: $1.36 \times 10^4$
Location: 2.0 X/D

Digital Imaging
- 'Outer Interface' Edges
- 'Ensemble Interface' Edges

Figure 44a. 'Outer' and 'Ensemble' Interface Distributions

Reynolds No.: $1.36 \times 10^4$
Location: 4.0 X/D

Digital Imaging
- 'Outer Interface' Edges
- 'Ensemble Interface' Edges

Figure 44b. 'Outer' and 'Ensemble' Interface Distributions
Reynolds No.: $1.36 \times 10^4$
Location: 8.0 X/D

Digital Imaging

- 'Outer Interface' Edges
- 'Ensemble Interface' Edges

**Figure 44c. 'Outer' and 'Ensemble' Interface Distributions**

Reynolds No.: $1.36 \times 10^4$
Location: 6.0 X/D

Digital Imaging

- 'Outer Interface' Edges
- 'Ensemble Interface' Edges

**Figure 44d. 'Outer' and 'Ensemble' Interface Distributions**
Reynolds No.: $1.36 \times 10^4$
Location: 10.0 X/D

Digital Imaging

- 'Outer Interface' Edges
- 'Ensemble Interface' Edges

Figure 44e. 'Outer' and 'Ensemble' Interface Distributions
Figure 45a. Interface Multi-Valuedness Distributions

Figure 45b. Cumulated Interface Multi-Valuedness Distributions
Figure 46a. Digital Imaging Outer Interface Distributions

Reynolds No.: 1.36 * 10^4  
Location: 6.0 X/D  
Sample Size: 5,000  
Mean Outer Edge Location, 1.70 D  
Variance, 0.86 D  
Skewness, 0.85  
Kurtosis, 0.71

Figure 46b. Digital Imaging Outer Interface Distributions

Reynolds No.: 1.36 * 10^4  
Location: 6.0 X/D  
Sample Size: 40,000  
Mean Outer Edge Location, 1.65 D  
Variance, 0.86 D  
Skewness, 0.71  
Kurtosis, 0.23
Reynolds No.: 1.36 \times 10^4  
Location: 6.0 X/D  
Sample Size: 10,000  
Mean Outer Edge Location, 0.09 D  
Variance, 1.68 D

Figure 47a. 'Combined' Outer Interface Distributions

Reynolds No.: 2.73 \times 10^4  
Location: 6.0 X/D  
Sample Size: 40,000  
Mean Outer Edge Location, 0.23 D  
Variance, 0.59 D

Figure 47b. 'Combined' Outer Interface Distributions
Figure 48a. Digital Imaging Outer Interface Distributions

Reynolds No.: $1.36 \times 10^4$
Mean Outer Edge Location, 1.07 D
Location: 2.0 X/D
Sample Size: 5,000
Variance, 0.32 D
Skewness, 0.43
Kurtosis, 0.59

Figure 48b. Digital Imaging Outer Interface Distributions

Reynolds No.: $1.36 \times 10^4$
Mean Outer Edge Location, 1.42 D
Location: 4.0 X/D
Sample Size: 5,000
Variance, 0.65 D
Skewness, 0.68
Kurtosis, 0.22
Reynolds No.: $1.36 \times 10^4$
Mean Outer Edge Location: 1.73 D
Location: 6.0 X/D
Sample Size: 5,000
Variance: 0.82 D
Skewness: 0.73
Kurtosis: 0.50

Figure 48c. Digital Imaging Outer Interface Distributions

Reynolds No.: $1.36 \times 10^4$
Mean Outer Edge Location: 2.10 D
Location: 8.0 X/D
Sample Size: 5,000
Variance: 0.84 D
Skewness: 0.71
Kurtosis: 0.63

Figure 48d. Digital Imaging Outer Interface Distributions
Reynolds No.: $1.36 \times 10^4$

Mean Outer Edge Location, 2.38 D

Location: 10.0 X/D

Sample Size: 5,000

Variance, 0.86 D

Skewness, 0.65

Kurtosis, 0.77

Figure 48e. Digital Imaging Outer Interface Distributions

---

Reynolds No.: $1.36 \times 10^4$

Mean Outer Edge Location, 2.50 D

Location: 12.0 X/D

Sample Size: 5,000

Variance, 0.90 D

Skewness, 0.69

Kurtosis, 1.02

Figure 48f. Digital Imaging Outer Interface Distributions
Digital Imaging

- Reynolds No.: $1.36 \times 10^4$, — Variance
- Reynolds No.: $6.82 \times 10^3$, — Variance

Figure 49a. Mean Outer Interface Locations
Figure 49b. Mean Outer Interface Locations - Variance

Figure 49c. Mean Outer Interface Locations - Skewness
Figure 49d. Mean Outer Interface Locations - Kurtosis

Reynolds No.: $1.36 \times 10^4$

Digital Imaging

Figure 50. Wake Centreline Crossing Extent Comparison

Reynolds No.: $1.36 \times 10^4$

Digital Imaging

Spectral Analysis

'Outer Interface'

Digital Imaging

'Spectral Analysis'
Reynolds No.: $1.36 \times 10^4$
Location: $2.0X/D$

- Intermittency
- Normalised Velocity Deficit

\[ \frac{y_0}{l_0} = 1.56, \quad \frac{a_0}{y_0} = 0.453 \]

Figure 51a. Normalised Mean Velocity Deficit and Intermittency

Reynolds No.: $1.36 \times 10^4$
Location: $4.0X/D$

- Intermittency
- Normalised Velocity Deficit

\[ \frac{y_0}{l_0} = 1.88, \quad \frac{a_0}{y_0} = 0.504 \]

Figure 51b. Normalised Mean Velocity Deficit and Intermittency
Reynolds No.: $1.36 \times 10^4$
Location: $6.0 \times D$

- Intermittency
- Normalised Velocity Deficit

$y_0/l_0 = 2.16, \sigma_0/y_0 = 0.454$

**Figure 51c. Normalised Mean Velocity Deficit and Intermittency**

Reynolds No.: $1.36 \times 10^4$
Location: $8.0 \times D$

- Intermittency
- Normalised Velocity Deficit

$y_0/l_0 = 1.96, \sigma_0/y_0 = 0.424$

**Figure 51d. Normalised Mean Velocity Deficit and Intermittency**
Reynolds No.: $1.36 \times 10^4$
Location: $10.0 \times D$

- Intermittency
- Normalised Velocity Deficit

$y_0/l_0 = 1.89$, $\sigma/y_0 = 0.409$

---

Reynolds No.: $1.36 \times 10^4$
Location: $12.0 \times D$

- Intermittency
- Normalised Velocity Deficit

$y_0/l_0 = 1.74$, $\sigma/y_0 = 0.404$

---

Figure 51e. Normalised Mean Velocity Deficit and Intermittency

Figure 51f. Normalised Mean Velocity Deficit and Intermittency
**Figure 52.** Entrainment Constant and Entrainment Percentage

**Figure 53.** Normalised Mass Flux, Mean Wake Location and Variance
Reynolds No.: $1.36 \times 10^4$
Location: 2.0 X/D
Sample Size: 5,000 'Left' Interface Statistics

Transverse Interface Velocity Mean, -0.01 Pixels
Variance, 20.91 Pixels
Skewness, 0.42
Kurtosis, 0.11

Transverse Interface Acceleration Mean, -0.28 Pixels
Variance, 32.85 Pixels
Skewness, -0.71
Kurtosis, 0.49

Figure 54a. Digital Imaging Interface Velocity & Acceleration
Figure 54b. Digital Imaging Interface Velocity & Acceleration
Reynolds No.: $1.36 \times 10^4$
Location: 10.0 X/D
Sample Size: 5,000 'Left' Interface Statistics

Transverse Interface Velocity Mean, -0.03 Pixels
Variance, 51.60 Pixels
Skewness, -0.18
Kurtosis, 0.39

Transverse Interface Acceleration Mean, -0.09 Pixels
Variance, 83.08 Pixels
Skewness, -0.46
Kurtosis, 0.47

Figure 54c. Digital Imaging Interface Velocity & Acceleration
Digital Imaging Interface Velocity Variance (D)

Reynolds No.: $1.36 \times 10^4$

- Interface Transverse Velocity
- Interface Transverse Acceleration

Figure 55a. Interface Velocity & Acceleration - Variance

Digital Imaging Interface Velocity Skewness

Reynolds No.: $1.36 \times 10^4$

- Interface Transverse Velocity
- Interface Transverse Acceleration

Figure 55b. Interface Velocity & Acceleration - Skewness
Reynolds No.: $1.36 \times 10^4$

- Interface Transverse Velocity
- Interface Transverse Acceleration

Figure 55c. Interface Velocity & Acceleration - Kurtosis
Reynolds No.: $1.36 \times 10^4$
Location: 2.0 X/D

- Turbulent Digital Imaging
- Non-Turbulent Digital Imaging

Figure 56a. Non-Turbulent/Turbulent Intermittency Distributions

Reynolds No.: $1.36 \times 10^4$
Location: 4.0 X/D

- Turbulent Digital Imaging
- Non-Turbulent Digital Imaging

Figure 56b. Non-Turbulent/Turbulent Intermittency Distributions
Reynolds No.: $1.36 \times 10^4$
Location: 6.0 X/D

- Turbulent Digital Imaging
- Non-Turbulent Digital Imaging

Figure 56c. Non-Turbulent/Turbulent Intermittency Distributions

Reynolds No.: $1.36 \times 10^4$
Location: 8.0 X/D

- Turbulent Digital Imaging
- Non-Turbulent Digital Imaging

Figure 56d. Non-Turbulent/Turbulent Intermittency Distributions
Reynolds No.: $1.36 \times 10^4$
Location: $10.0 \times D$

- Turbulent Digital Imaging
- Non-Turbulent Digital Imaging

Figure 56e. Non-Turbulent/Turbulent Intermittency Distributions

Reynolds No.: $1.36 \times 10^4$

- Digital Imaging

Figure 57. Non-Turbulent/Turbulent Intermittency Percentage
Figure 58a. Normalised Turbulence Distributions

Reynolds No.: $1.36 \times 10^4$
Location: 2.0 X/D

Figure 58b. Normalised Turbulence Distributions

Reynolds No.: $1.36 \times 10^4$
Location: 4.0 X/D
Reynolds No.: $1.36 \times 10^4$
Location: 6.0 X/D

- Digital Imaging
- 'Combined' Hot-Wire
- 'Turbulent' Hot-Wire

Figure 58c. Normalised Turbulence Distributions

Reynolds No.: $1.36 \times 10^4$
Location: 8.0 X/D

- Digital Imaging
- 'Combined' Hot-Wire
- 'Turbulent' Hot-Wire

Figure 58d. Normalised Turbulence Distributions
Figure 58e. Normalised Turbulence Distributions

Reynolds No.: $1.36 \times 10^4$
Location: $10.0 \times D$

- Digital Imaging
- 'Combined' Hot-Wire
- 'Turbulent' Hot-Wire

Figure 58f. Normalised Turbulence Distributions

Reynolds No.: $1.36 \times 10^4$
Location: $12.0 \times D$

- Digital Imaging
- 'Combined' Hot-Wire
- 'Turbulent' Hot-Wire
Figure 59a. Corrected Normalised Turbulence Distributions

Reynolds No.: $1.36 \times 10^4$
Location: 6.0 X/D

Digital Imaging
Corrected Hot-Wire

Figure 59b. Corrected Normalised Turbulence Distributions

Reynolds No.: $1.36 \times 10^4$
Location: 10.0 X/D

Digital Imaging
Corrected Hot-Wire
Reynolds No.: $1.36 \times 10^4$

- Digital Imaging
- Hot-Wire

Figure 60. Comparative Centreline Turbulence Decay
Smoke Injection

Cylinder Model (PVC Waste Pipe No. 200)

Cylinder Smoke Holes 1.5Ø

Detail A

Smoke Tube 21.5Ø

42.5 O.D.

38.0 I.D.

1.5Ø Holes

Perspex Sealing Rings with 'O'-ring Seals

1.5Ø Holes

Copper Smoke Tube

All Dimensions in mm.

Figure 61. Circular Cylinder Model

Figure 62. Circular Cylinder Shedding Frequency Relationship
Reynolds No.: $2.85 \times 10^3$
Location: 1.5d

Figure 63. Digital Imaging Cylinder Frequency Analysis
Reynolds No.: $4.28 \times 10^3$
Location: 1.5d

Figure 64. Hot-Wire Cylinder Frequency Analysis
Figure 65. Secondary Vortex Shedding Frequency vs Velocity

- Wei and Smith (1986) Predicted

\[ \frac{f_1}{f_v} = \left( \frac{\text{Re}}{470} \right)^{0.87} \]

Figure 66. Non-Dimensional Shedding Frequency vs Re - Log Axes
Figure 67. **Secondary Vortex Shedding Frequency vs Bleed Rate**

**, Digital Imaging

![Graph showing Secondary Vortex Shedding Frequency vs Fan Voltage (V).](image)

**Figure 68. Schematic of Jet in a Cross-Flow Arrangement**

- Centrifugal Fan
- Jet/Freestream Velocity 4:1
- Circular Jet Diameter \(d\), 19.05 I.D.
- Measuring Station A-A
- All Dimensions in mm.
Figure 69. Iso-Intermittency Map of Jet Cross-Section

Downstream Location 6.5d

Transverse Section of Scalar Field

Jet/Freestream Ratio 8:1

Taken from Sykes et al. (1986)

Figure 70. Comparative Scalar Distribution in Jet Cross-Section
Figure 71. Schematic of Flat Plate Boundary Layer Model

Figure 72. Schematic of Large-Eddy Breakup Devices (LEBUs)
Boundary Layer Profile - LEBU Station
Freestream Velocity: 1.0 m/s (No LEBU)
Velocity Profile: \( u = \left( \frac{y}{28} \right)^{1/4} \times 78 \)

\( \delta^* = 4.81 \text{ mm} \)
\( \theta = 3.06 \text{ mm} \)
\( H = 1.57 \)
\( \delta_{0.99} = 28.0 \text{ mm} \)

Figure 73. Mean Longitudinal Velocity Profile - LEBU Station

Boundary Layer Profile - Measurement Station
Freestream Velocity: 1.0 m/s (No LEBU)
Velocity Profile: \( u = \left( \frac{y}{36} \right)^{1/4} \times 88 \)

\( \delta^* = 6.03 \text{ mm} \)
\( \theta = 3.91 \text{ mm} \)
\( H = 1.54 \)
\( \delta_{0.99} = 36.0 \text{ mm} \)

Figure 74. Mean Longitudinal Velocity Profile - Test Station
Boundary Layer Profile - Measurement Station
Freestream Velocity: 1.0m/s (10mm LEBU height)
Non-Dimensional LEBU height (1/δ) = 0.36

Figure 75a. Mean Velocity and Turbulence Profiles - Test Station
Boundary Layer Profile - Measurement Station
Freestream Velocity: 1.0 m/s (15 mm LEBU height)
Non-Dimensional LEBU height (1/δ) = 0.54

Mean Longitudinal Velocity (u/\text{Uref})

Distance from Plate (mm)

Turbulence Intensity (%)

Distance from Plate (mm)

Figure 75b. Mean Velocity and Turbulence Profiles - Test Station
Boundary Layer Profile - Measurement Station
Freestream Velocity: 1.0m/s (20mm LEBU height)
Non-Dimensional LEBU height ($1/\delta$) = 0.71

Figure 75c. Mean Velocity and Turbulence Profiles- Test Station
Boundary Layer Profile - Measurement Station
Freestream Velocity: 1.0m/s (25mm LEBU height)
Non-Dimensional LEBU height (1/δ) = 0.89

Figure 75d. Mean Velocity and Turbulence Profiles - Test Station
Figure 76. Flat Plate Model used for Shear Stress Measurements

Figure 77. Shear Stress vs Relative Pixel Intensities